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Abstract

The observed characteristics of globular cluster (GC) systems, such as metallicity distributions, are commonly used to place constraints on galaxy formation models. However, obtaining reliable metallicity values is particularly difficult because of our limited means to obtain high quality spectroscopy of extragalactic GCs. Often, “color–metallicity relations” are invoked to convert easier-to-obtain photometric measurements into metallicities, but there is no consensus on what form these relations should take. In this paper we make use of multiple photometric data sets and iron metallicity values derived from applying full-spectrum stellar population synthesis models to deep Keck/LRIS spectra of 177 GCs centrally located around M87 to obtain a new color–metallicity relation. Our new relation differs substantially from previous relations in the blue, and we present evidence that the M87 relation differs from that of the Milky Way GCs, suggesting environmental dependence of GC properties. We use our color–metallicity relation to derive a new GC metallicity–host galaxy luminosity relation for red and blue GCs and find a shallower relation for the blue GCs than what previous work has found and that the metal-poor GCs are more enriched than what was previously found. This could indicate that the progenitor satellite galaxies that now make up the stellar halos of early-type galaxies are more massive and formed later than previously thought, or that the properties of metal-poor GCs are less dependent on their present-day host, indicating a common origin.

Key words: galaxies: evolution – galaxies: individual (M87) – galaxies: star clusters: general

1. Introduction

Although Λ CDM cosmology gives us the broad framework that galaxies form hierarchically, the details of how giant early-type galaxies (ETGs) form is still a matter of debate. Areas of ongoing uncertainty include the assembly of ETGs such as the epoch of the last merger and what kind of progenitor galaxies now constitute the stellar halos of ETGs. In particular, while cosmological simulations point to massive progenitor satellites as building the stellar halos of present-day giant ETGs (see, for example, Figure 13 of Pillepich et al. 2018), observational constraints suggest dwarf galaxies as the progenitors (Figure 2 of Forbes et al. 2015).

Globular clusters (GCs) are nearly ubiquitous around galaxies and have been determined to be old (~ 10 Gyr) in a variety of systems (see references in Brodie & Strader 2006). Those properties as well as their luminosity ($-5 < M_V < -10$) make them potentially useful tracers of galaxy formation and assembly. However, the promise of GCs in this capacity has yet to be fully realized, in part, because of our limited means to understand the present-day physical properties of GC systems.

van den Bergh (1975) first used the likely connection between a galaxy’s star formation episodes and its GC population to suggest a link between galaxy luminosity and the metallicities of its GCs. This relation was confirmed by Brodie & Huchra (1991), and subsequently the paradigm of *bimodality* has overtaken the extragalactic GC field. Bimodality was first established through optical color distributions from *Hubble Space Telescope* photometry (Gebhardt & Kissler-Patig 1999; Kundu & Whitmore 2001a; Larsen et al. 2001). Since then GC systems around ETGs are treated as composed from two subpopulations and separately track the

subpopulation characteristics with host galaxy characteristics to place constraints on galaxy formation scenarios (e.g., Côté et al. 2002; Rhode et al. 2005; Strader et al. 2005; Li & Gnedin 2014). Recently though, Harris et al. (2017) presented observational evidence that the most massive ETGs, brightest cluster galaxies, can have broad unimodal distributions in addition to bimodal distributions.

GCs are thought to contain coeval stars with old ages and mostly homogenous metallicities and so broadband colors of GCs are generally considered to reflect their underlying mean metallicity. The simplicity of this logic belies the fact that there is no consensus on how broadband colors should be transformed into metallicities (parameterized as the “color–metallicity relation”). The core of almost all astronomical problems is translating observed characteristics into physically meaningful properties and understanding GC systems is no exception. We have very limited means to obtain spectroscopy—our best observational tool for deriving physical stellar population characteristics—of individual GCs around the largest elliptical galaxies. This is a result of a two-fold problem: at the distances of elliptical galaxies, GCs are faint, and the largest elliptical galaxies can host systems of tens of thousands of GCs. This means that in extragalactic work we often only have access to coarse observational characteristics of individual GCs, such as broadband photometry.

The problems associated with obtaining the metallicity distribution are illustrated through the difference between the Harris et al. (2006) and Peng et al. (2006) color–metallicity relations. Peng et al. (2006) used *HST*/ACS photometry of GCs around Virgo Cluster galaxies from Jordán et al. (2004) and metallicities gathered from the few spectroscopic studies of extragalactic GCs (Cohen et al. 1998, 2003). Peng et al. (2006)

found a color–metallicity relation with a significant break when transitioning to the blue GCs but crucially their relation was based almost entirely on Milky Way GCs at the metal-poor end. Harris et al. (2006) derived a linear relation between $B - I$ colors and metallicities for Milky Way GCs to interpret the broadband colors they obtained for Virgo Cluster GC systems. Peng et al. (2006) and Harris et al. (2006) reported essentially the same color distributions for the Virgo GC systems but different metallicity distributions.

Despite their differences, both Peng et al. (2006) and Harris et al. (2006) both maintained evidence for metallicity bimodality but that paradigm was challenged by Yoon et al. (2006). Yoon et al. (2006) introduced the idea of generating synthetic color–metallicity relations to transform the overall color distributions of GC systems to metallicity distributions. They found that highly nonlinear color–metallicity relations, like those that result from inclusion of helium-rich hot horizontal branch stars, can transform unimodal metallicity distributions into bimodal color distributions.

Contrary to Yoon et al. (2006) and their follow-up work (Lee et al. 2019), studies that directly model the spectroscopic observations of GCs consistently find bimodal metallicity distributions (Alves-Brito et al. 2011; Brodie et al. 2012; Usher et al. 2012). But the differences between the Harris et al. (2006) and Peng et al. (2006) color–metallicity relations and the color–metallicity relations determined for the systems included in the Usher et al. (2012) sample highlight that there appear to be other physical properties that affect broadband colors than just metallicity.

Full-spectrum stellar population synthesis (SPS) modeling provides a way to move past these problems. Modern full-spectrum models allow for variations in abundance patterns (Conroy et al. 2014) over a variety of ages (Choi et al. 2014) and metallicities (Conroy et al. 2018). In addition to fully accounting for possible variations in many stellar population parameters we have shown that full-spectrum fitting allows us to extract information from data in a lower signal-to-noise ratio (S/N) regime than traditional index fitting (Conroy et al. 2018).

It is exactly this last property of full-spectrum SPS models that enables us to make use of the Strader et al. (2011) database of spectroscopy of individual GCs around M87. In this paper we present the most comprehensive and accurate compendium of metallicities of individual GCs around M87 (which we describe in Section 2). We use these metallicities to derive a new color–metallicity relation in Section 3. We discuss the implications of the new color–metallicity relation in Section 4.

2. SPS Modeling

We make use of the Keck/LRIS spectroscopic subsample of the data set described in Strader et al. (2011; $\sim 3300\text{--}5600\text{ \AA}$). In the top panel of Figure 1 we show a deep image of M87 from the Burrell Schmidt Deep Virgo Survey (Mihos et al. 2017) with the NGVS photometric catalog (yellow; Oldham & Auger 2016), the ACSVCS photometric catalog (green; Jordán et al. 2009), and the LRIS spectroscopic sample (blue; Strader et al. 2011).

There are several features of the Strader et al. (2011) sample that are salient to the work presented in this paper. First, the clusters in this sample were chosen to be fainter in magnitude than the obvious “blue-tilt” clusters, which will help when we assess bimodality. Second, in the bottom left panel of Figure 1 we compare the NGVS photometry sample with the

LRIS sample in color–magnitude space. The LRIS sample spans nearly the whole color range of the M87 GC system (middle panel Figure 1).

This work makes use of the updated full-spectrum SPS models (alf) described in Conroy et al. (2018). The most relevant update of the Conroy et al. (2018) models with regards to this work is the expansion of stellar parameter coverage of the models with the Spectral Polynomial Interpolator (SPI; Villaume et al. 2017b).⁵ With SPI we used the optical MILES stellar library (Sánchez-Blázquez et al. 2006), the Extended IRTF stellar library (E-IRTF; Villaume et al. 2017b), and a large sample of M Dwarf spectra (Mann et al. 2015) to create a data-driven model that we can use to generate stellar spectra as a function of effective temperature, surface gravity, and metallicity.

The empirical parameter space is set by the E-IRTF and Mann et al. (2015) samples, which together span $-2.0 \lesssim [\text{Fe}/\text{H}] \lesssim +0.5$ and $3.9 \lesssim \log T_{\text{eff}} \lesssim 3.5$. To preserve the quality of interpolation at the edges of empirical parameter space we augment the training set with a theoretical stellar library (C3K). The alf models allow for variable abundance patterns by differentially including theoretical element response functions. In Conroy et al. (2018) we fitted the Schiavon et al. (2005) spectroscopic sample of Milky Way GCs and compared the alf-inferred $[\text{Fe}/\text{H}]$ values with a compilation of $[\text{Fe}/\text{H}]$ values from the literature (see Roediger et al. 2014 for details). Over a range of $-2.5 \lesssim [\text{Fe}/\text{H}] \lesssim +0.0$ we had nearly one-to-one consistency between the literature values and our measured $[\text{Fe}/\text{H}]$ values from integrated light (specifically, $[\text{Fe}/\text{H}]_{\text{lit}} \propto 1.06[\text{Fe}/\text{H}]_{\text{alf}}$).

The LRIS sample is in the low-S/N regime with $\sim 5\text{--}30$ encompassing the range of the median S/N over each spectrum (bottom right panel in Figure 1). In this modest S/N regime it is difficult to obtain accurate stellar population parameters (Sánchez-Blázquez et al. 2011). To obtain an accurate color–metallicity relation we need the metallicities of individual GCs and therefore stacking spectra is not a good option for this particular problem.

We fit objects using both full-spectrum (left) and traditional line-index methods (right). For our line-index fits we use the canonical set of Lick indices (Faber et al. 1985; Burstein et al. 1986; Worthey et al. 1994): $\text{H}\delta_F$, CN_2 , $\text{Ca}4227$, $\text{G}4300$, $\text{H}\gamma_F$, $\text{Fe}4383$, $\text{Fe}4531$, C_24668 , $\text{H}\beta$, $\text{Fe}5015$, Mgb , $\text{Fe}5270$, $\text{Fe}345$, and $\text{Fe}5406$. For the full-spectrum fits we fit in simple-mode over the wavelength regions: $3900\text{--}4400\text{ \AA}$, $4400\text{--}4900\text{ \AA}$, and $4900\text{--}5200\text{ \AA}$. We smoothed the LRIS spectra to be a constant 200 km s^{-1} over the whole wavelength range.

In Figure 2 we demonstrate the utility of full-spectrum fitting over line-index methods. In this figure we compare $[\text{Fe}/\text{H}]$ posteriors for metal-rich GCs (left column) and metal-poor GCs (right column) where the spectrum were fitted using the full spectrum (top row) and Lick indices (bottom row). In each panel we compare the results of high-S/N and low-S/N spectra. We demonstrate that in both the metal-rich and metal-poor cases the posteriors are better constrained when full-spectrum fitting is used. In the metal-rich case, the posterior distributions for high- and low-S/N using Lick indices have larger tails than the posterior distributions from full-spectrum fitting. The real utility of the new models is shown in the low-metallicity case where the posterior distributions are more centered on a single value from full-spectrum fitting than from indices.

⁵ https://github.com/AlexaVillaume/SPI_Utils

Figure 1. (Top) Image of M87 from the Burrell Schmidt Deep Virgo Survey (Mihos et al. 2017) with spatial distributions of the NGVS photometry (yellow), ACSVCS photometry (green), and LRIS spectroscopy (blue). (Bottom left) Color-magnitude diagram for the M87 GCs from the NGVS catalog from Oldham & Auger (2016; gray), the culled sample of the LRIS data set (red) from Strader et al. (2011). (Bottom right) Histogram of median signal-to-noise ratio values for the individual spectra of the LRIS sample.

Figure 2. Comparing $[\text{Fe}/\text{H}]$ posteriors for metal-rich GCs (left column) and metal-poor GCs (right column) where the spectra were fitted using the full spectrum (top row) and Lick indices (row). In all cases the full-spectrum fits provide better constraints on $[\text{Fe}/\text{H}]$ than index fits. For the metal-rich GCs, the index fits have broader tails than the full-spectrum fits of the same GCs. For the metal-poor GCs, the index fits do not result in well-behaved posterior distributions on $[\text{Fe}/\text{H}]$. The GCs in this figure correspond to the GCs in Figures 3 and 4.

In Figures 3 and 4 we examine the quality of our fits for metal-rich and metal-poor GCs, respectively. In each figure we compare the LRIS spectrum (black) with the best-fit model spectrum for a high-S/N (brown) spectrum and a low-S/N (green) spectrum in the top panel. The middle and bottom panels in each figure compare the residuals between the high-S/N spectra and low-S/N, respectively, with the flux uncertainty of each LRIS spectrum (gray band). These comparisons demonstrate that the fitting was successful as the residuals are consistent with the flux uncertainty. Even with the low-S/N spectra several spectral features are still prominent; Ca II, H δ , H β , and Mg b are well-characterized by the best-fit model.

After we fit every spectrum we visually inspected the residuals between the observed spectrum and the best-fit model. From this inspection we identified cases where the best-fit model is clearly a poor fit to the data. We removed these clusters from our subsequent analysis, bringing our final sample to 177 GCs. Of the 23 GCs we culled from our final metallicity sample, 20 have NGVS photometry, and 15 of those are considered to be blue ($g-z < 1.0$). This suggests that it is more difficult to obtain adequate spectra of the blue and,

presumably, metal-poor GCs but with our remaining blue GCs we are still adequately covering the metal-poor parameter space. The posteriors for the $[\text{Fe}/\text{H}]$ values for the final sample of GCs are available at <https://github.com/AlexaVillaume/m87-gc-feh-posteriors>.

3. Results

3.1. Comparison to Previous Work

Cohen et al. (1998) previously performed a stellar population analysis on a spectroscopic sample of M87 GCs (Cohen & Ryzhov 1997) using indices to determine metallicity values. To aid our analysis we matched the Cohen et al. (1998) sample to the Oldham & Auger (2016) NGVS-based photometry catalog. We matched the Cohen et al. (1998) sample to the data presented in Hanes et al. (2001), which provided R.A. and decl. values for all the GCs in the Strom et al. (1981) catalog that Cohen & Ryzhov (1997) selected their targets from.

Then we used the position values to match with the Oldham & Auger (2016) catalog with a max separation of $1''$. We dereddened the Oldham & Auger (2016) photometry using the Fitzpatrick (1999) extinction law and extinction values taken

Figure 3. Top: comparison of metal-rich ($[\text{Fe}/\text{H}] > +0.1$) LRIS spectra (black) and best-fit models for a high-S/N (H51142, $(g-z)_{\text{NGVS}} = +1.38$, brown) observation and a low-S/N (H51943, $(g-z)_{\text{NGVS}} = +1.33$, green). Middle: comparison of residuals between best-fit model and data for H51075 and uncertainty of flux from the input spectrum (gray). Bottom: same as middle panel but for H51943.

from the Schlegel et al. (1998) dust map using the NASA/IPAC Infrared Science Archive ($A_g = 0.087$, $A_i = 0.048$, $A_z = 0.034$, $R_g = 3.793$, $R_i = 2.086$, $R_z = 1.479$).

We do not include the objects in Table 1 of Cohen & Ryzhov (1997) and not every GC in the Cohen et al. (1998) sample has NGVS photometry so we go from the full Cohen et al. (1998) sample of 150 GCs with $[\text{Fe}/\text{H}]$ values to 101 GCs. In the left panel of Figure 5 we compare the normalized cumulative metallicity distributions of both the full (blue) and matched (orange) Cohen et al. (1998) sample. This comparison demonstrates that we are not biasing the Cohen et al. (1998) sample by doing the matching.

In Figure 6 we compare our final sample of 177 GCs to the photometry-matched Cohen et al. (1998) sample. In the left panel we compare the cumulative brightness distributions of each sample. In the middle panel we compare the NGVS ($g-z$) colors of the two samples. In the right panel we compare the cumulative metallicity distributions of both samples. We see that $\sim 40\%$ of the objects in our sample are fainter than the faintest GC included in the Cohen et al. (1998) sample. The range of colors spanned by each sample are similar but the Cohen et al. (1998) sample has a different overall distribution than our sample. More importantly, we see that from the way the curves change from color to metallicity that the Cohen et al. (1998) color-metallicity relation will be different from ours. Furthermore, the Cohen et al. (1998) metallicities are, on the whole, lower than our metallicities. We discuss the nature of this last difference in more detail in Section 4.1.

3.2. Updated Color-Metallicity Relationships

We use two photometric data sets of the M87 GC system: the Oldham & Auger (2016) catalog of ground-based photometry

using the NGVS survey data (Ferrarese et al. 2012) and photometry from the ACS Virgo Cluster Survey (ACSVCS) from Jordán et al. (2009). We use the g - and z -band filters from each survey but it is important to note that the filters are not identical between the two instruments (see Figure 7) and so the color-metallicity relationships for the two instruments will be slightly different.

Our sample of 177 spectroscopically derived $[\text{Fe}/\text{H}]$ values overlaps with 172 objects from the NGVS catalog but only 37 of the GCs with spectroscopically derived metallicities overlap with the ACSVCS catalog. To mitigate any problems that might arise from such a sparse sample we leverage the fact that the underlying α lf models extend over a wider wavelength range than the LRIS data and are flux calibrated (see Villaume et al. 2017b; Conroy et al. 2018, for discussion).

We used the flux-calibrated models that correspond to the inferred stellar parameters for each individual GC to compute synthetic photometry for both the ACSVCS and NGVS bandpasses. In Figure 7 we show the relation between the synthetic photometry using the different filter systems. We also show our best-fit line to the data (excluding the outliers marked with the open circles) so that the colors of GCs can be transformed from one system to the other. GCs identified as outliers by the regression model are marked with open circles. The outliers from this relation are just the result of numerical problems for these particular clusters in generating models over the available wavelength range. As can be seen in Figure 7, the overwhelming majority of the GCs follow a tight relation between the ACSVCS filter system and the NGVS system.

In Figure 8 we show the color-metallicity relations using the NGVS (left) and ACSVCS (right) photometry for both the observed (top) and the synthetic (bottom) $g-z$ colors. We fit all

Figure 4. Same as for Figure 3 but for the metal-poor GCs (<-1.5) H38032 ($(g-z)_{\text{NGVS}} = +0.70$, brown) and H42981 ($(g-z)_{\text{NGVS}} = +0.69$, green).

Figure 5. Comparing the complete sample of M87 GC metallicities from Cohen et al. (1998) (140 GCs, blue) with the sample when matched to the Oldham & Auger (2016) photometry (101 GCs, orange) to demonstrate that we are not biasing the Cohen et al. (1998) metallicity distribution by matching to photometry.

four color–metallicity relations using linear regression in a Bayesian framework with outlier pruning and uncertainty weighting (see Hogg et al. 2010 for details) and show the best-fit lines for each relation and 100 samples drawn from the posteriors in each panel (orange lines).

We demonstrate that there is good agreement between the relations using observed and synthetic NGVS photometry. This is important because this assures us of the quality of the synthetic color–metallicity relation for the ACS photometry.

The relation using the observed ACSVCS photometry has large uncertainties because of the sparsity of the sample.

Any outliers detected by the fitting algorithm are highlighted by red open circles in each panel. The regression fits do not include those points. Linearity is a good representation of the data in all four cases. We fit the data with a quadratic relation, which was not statistically preferred over the linear relation in any case. In Table 1 we list the median and standard deviation of slope and intercept values of each relation.

In Figure 9 we show the normalized histograms of the residuals between the observed $[\text{Fe}/\text{H}]$ values and the values predicted by the best-fit color–metallicity relations divided by the observed $[\text{Fe}/\text{H}]$ uncertainties. In each panel we show a standard normal distribution and indicate in the legend the measured mean and variance of the residual distribution. The residuals have a larger variance than what is expected from a standard normal distribution. This is likely because the color–metallicity relations have genuine spread because GC systems are an amalgamation of different stellar populations.

In the right panels of Figure 8 we also show the Peng et al. (2006) relation. Our relation is consistent with Peng et al. (2006) for the red ($g-z > 1.0$) GCs but differs significantly for the blue GCs. We already noted in the previous section that the Cohen et al. (1998) metallicities used by Peng et al. (2006) are more metal-poor as a whole than the metallicities that we have derived for the M87 GCs. Peng et al. (2006) also supplemented their sample with Milky Way GCs.

To understand how the presence of Milky Way GCs might have affected the color–metallicity relation we look at how the Milky Way GCs compare to the M87 GCs in Figure 10. We generated synthetic photometry for the Milky Way GCs to obtain ACS $g-z$ colors for the clusters. We show the color–metallicity relation using both the $[\text{Fe}/\text{H}]$ values we derived

Figure 6. Left: comparing the cumulative magnitude functions for the matched Cohen et al. (1998) sample and the sample from this work. Middle: same as left but for $(g-z)$. Right: same as left and middle but for $[\text{Fe}/\text{H}]$. Also in the right panel we show the distribution of $[\text{Fe}/\text{H}]$ values for Milky Way GCs from our full-spectrum fits to the Schiavon et al. (2005) data, which shows that the Milky Way GCs are typically more metal-poor than the M87 GCs.

Figure 7. Relation between synthetic NGVS and ACSVCS photometry for the spectroscopic sample. Since the two surveys are on slightly different filter systems we present a way to transform colors between each: $(g-z)_{\text{ACSVCS}} = 1.123(g-z)_{\text{NGVS}} - 0.015$.

from our fits to the Schiavon et al. (2005) spectroscopy (brown circles) and $[\text{Fe}/\text{H}]$ values compiled from various literature sources (Roediger et al. 2014, open green circles). We also show the M87 GCs (black points). We show the best-fit lines for the Milky Way GC color–metallicity relation (colored lines) and the Peng et al. (2006) relation (dashed black line). In the left panel we show the blue GCs and in the right panel we show the red GCs.

We see in Figure 10 that the blue Milky Way GCs have a different color–metallicity relation than the M87 GCs. The color–metallicity relations for the Milky Way GCs are closer to the Peng et al. (2006) relation, which makes sense because it is the Milky Way GCs that drive the blue end of Peng et al.’s (2006) relation. Moreover, Peng et al. (2006) used the Harris (1996) compilation of Milky Way GC $[\text{Fe}/\text{H}]$ values and we show that the color–metallicity relation using $[\text{Fe}/\text{H}]$ values from the literature is even closer to the Peng et al. (2006) relation than the relation using the spectroscopically derived $[\text{Fe}/\text{H}]$ values.

3.3. Metallicity Distributions

In Figure 11 we demonstrate the effect of our new color–metallicity relations on the derived metallicity distributions. In the left panel we compare the NGVS (yellow) and ACSVCS (green) color distributions. For NGVS we only show clusters within $R_{\text{gal}} < 30.5$ kpc to match the spatial extent of the spectroscopic data set. This comparison emphasizes the effect that the spatial extent of the data has on the analysis. In GC systems around massive galaxies, it has been established that the blue GCs begin to dominate further away from the center (e.g., Harris et al. 2017). The ACSVCS sample only extends to $R_{\text{gal}} \sim 13$ kpc and we see bimodality clearly in the color distribution for that sample. Meanwhile, the NGVS sample extends more than twice as far out and bimodality gets completely washed out in its color distribution.

In the middle panel we compare the spectroscopically derived metallicity distribution (gray) with the metallicity distributions derived from the ACSVCS and NGVS samples using their respective color–metallicity relations for two galactocentric radius cutoffs: $R_{\text{gal}} < 30.5$ kpc (green) and $R_{\text{gal}} < 10.5$ kpc (black dashed). We removed those GCs that are in both samples from the NGVS sample. The photometrically derived MDF appears to be consistent with the spectroscopically derived MDF but gives a less noisy view of the MDF. The MDF where we truncate at $R_{\text{gal}} = 10.5$ kpc more obviously displays bimodality than the MDF where the sample extends further out.

In the right panel we compare the metallicity distributions derived from the ACSVCS and NGVS colors to the metallicity distribution derived from applying the Peng et al. (2006) color–metallicity relation to the ACSVCS data only (gray). We see that the different color–metallicity relations lead to drastically different MDFs. The peak of the metal-poor subpopulation is more metal-rich in MDF established in this work and the dispersions of both subpopulations are very different between the different MDFs.

In Figure 12 we see the importance of the new color–metallicity relations derived in this work. In the left panel we show the mean values of the blue and red GC populations as a function of host galaxy luminosity in seven bins of host galaxy magnitude for the Virgo Cluster galaxies included in the Peng et al. (2006) analysis. In the right panel we have used the color–metallicity relation determined in this paper to

Figure 8. Top left: color–metallicity relation using observed NGVS $g-z$ colors for the 172 GCs that are in both the spectroscopic sample and NGVS. Bottom left: same as top left with synthetic colors for all 177 GCs in the spectroscopic sample. Top right: color–metallicity relation using observed ACSVCS colors for the 37 GCs that are in both that and the spectroscopic sample. Bottom right: synthetic color–metallicity relation in the ACSVCS bands for all 177 GCs in the spectroscopic sample. In each panel we show the best-fit line and 100 samples drawn from the posterior distribution by fitting the corresponding data points with a linear model (see the text for details). In the right panels we show the Peng et al. (2006) relation (dashed green). The regression algorithm detects outliers in the data, which are shown in each plot by the red circles.

Table 1

Median Values of Posterior Distributions of Best-fit Line Parameters with Standard Deviations for Each Fit

	Slope	σ_{slope}	Intercept	$\sigma_{\text{intercept}}$	$\sigma_{\text{residuals}}$
ACSVCS (obs)	1.79	0.25	−2.77	0.31	2.14
ACSVCS (syn)	1.96	0.08	−2.88	0.10	2.70
NGVS (obs)	2.12	0.12	−2.92	0.13	2.62
NGVS (syn)	2.20	0.10	−2.90	0.11	2.69

Note. We also show the standard deviation of the residual $[\text{Fe}/\text{H}]$ distributions, $\sigma_{\text{residuals}}$.

transform the mean colors established in Peng et al. (2006) into mean metallicities. We derived uncertainties for the metallicity values by doing Monte Carlo sampling of the color–metallicity relation using the color uncertainties.

We show the linear fit to the new relations in the solid lines. We show the relations Peng et al. (2006) determined as dashed lines. As we would expect from the previous results, the new relation between host galaxy luminosity and mean metallicity for the metal-rich GCs is similar to the Peng et al. (2006) result but the relation for the metal-poor GCs is shallower and more metal-rich than the Peng et al. (2006) result.

Figure 9. Normalized histograms of the residuals between the observed $[\text{Fe}/\text{H}]$ values and the values predicted by the best-fit color–metallicity relations divided by the observed $[\text{Fe}/\text{H}]$ uncertainties. We have indicated the mean offset, μ , and standard deviation, σ for the distribution of residuals. A Gaussian distribution with $\sigma = 1$ is also shown.

Figure 10. We show synthetic ACS $g-z$ color vs. metallicity for the M87 clusters (black) and the Milky Way GCs. The inclusion of the MW GCs in the Peng et al. (2006) analysis explains much of the discrepancy between our color–metallicity relations.

4. Discussion

4.1. Which Metallicity Is It Anyway?

The difference between our and Peng et al.’s (2006) color–metallicity relationships is substantial for the blue GCs. We can understand this difference by examining the origin of the $[\text{Fe}/\text{H}]$ values Peng et al. (2006) used in their analysis. First, the Milky Way GCs make up the majority of the blue GCs used in the Peng et al. (2006) sample. We demonstrated in Figure 6 that the Milky Way GCs are more metal-poor than the M87 GCs. In Figure 10 we show that, using both literature $[\text{Fe}/\text{H}]$ values and $[\text{Fe}/\text{H}]$ values derived from full-spectrum fitting, the Milky Way GCs have a different color–metallicity relation than the M87 GCs. The closeness of the Peng et al. (2006) relation in the blue to the Milky Way GC relation is highly

suggestive that the presence of the Milky Way GCs is driving and biasing the relation in the blue for Peng et al. (2006).

Second, we show in Figure 6 that even though the GCs in our sample and the Cohen et al. (1998) sample span a similar color range, the Cohen et al. (1998) metallicity values are systematically lower than the metallicities we derive. There are no GCs that are shared between the Cohen et al. (1998) sample and our sample but we can understand the differences between the two by bearing in mind two related facts: the fitting functions that underlie the Worthey et al. (1994) models are not well-calibrated at high metallicities and the Cohen et al. (1998) metallicities are placed on the Zinn (1985) metallicity scale which is set by Milky Way GCs.

The former was discussed in Cohen et al. (2003) as a serious concern. Cohen et al. (2003) redid the $[\text{Fe}/\text{H}]$ determinations of

Figure 11. Left: distributions of the $(g-z)_0$ colors from NGVS (yellow) and ACSVCS (green). The ACSVCS sample is redder and more metal-rich than the NGVS sample on average because it is drawn from a more central region of the galaxy. We limited the NGVS sample to objects within $R_{\text{gal}} < 30.5$ kpc to match the footprint of the spectroscopic sample. Middle: comparing distributions of metallicity measured from spectroscopy (gray) and from our color-metallicity relationships including both NGVS and ACSVCS photometry where we truncate the sample to $R_{\text{gal}} < 30.5$ kpc (green) and $R_{\text{gal}} < 10.5$ kpc (black dashed). Objects in both samples were removed from the NGVS sample. Right: comparing the derived metallicity distributions from NGVS and ACSVCS with the metallicity distribution derived from the Peng et al. (2006) relation applied to the ACSVCS colors. The peak of the metal-poor subpopulations are dramatically different, which will affect comparisons to models.

Figure 12. Left: mean values of the blue and red GC colors as a function of host galaxy luminosity in seven bins of host galaxy magnitude (see Peng et al. 2006, for details). Right: mean metallicities of the blue and red GC populations using the color-metallicity relation determined in this work (solid lines) and the best-fit lines from Peng et al. (2006; dashed lines). The different color-color metallicity established in this work propagates to a dramatically different metal-poor relation.

the M87 GCs from Cohen et al. (1998) by extrapolating the models to higher metallicity by assuming that the indices are on the damping part of the curve of growth. This affected five M87 GCs in their sample. We are, to be clear, using the Cohen et al. (1998) metallicities in this work as Peng et al. (2006) did.

For the latter, Cohen et al. (1998) noted that from their qualitative analysis of the line indices for the Milky Way and M87 GCs that the M87 GCs have a metal-rich tail that extends to significantly higher metallicities than the Milky Way GCs, which we confirm. The relation they use to scale the Worthey et al. (1994) models to the Milky Way GCs is $[\text{Fe}/\text{H}]_{\text{Z}} = 0.760 \times [\text{Fe}/\text{H}]_{\text{W}} - 0.265$, which would lower the overall metallicity of their sample. Overall, we see that the Peng et al. (2006) relation is yoked to the Milky Way GCs in both explicit and implicit ways. The $[\text{Fe}/\text{H}]$ values that we present in this work come from the underlying isochrones (Choi et al. 2016)

and the underlying stellar library (Villaume et al. 2017b). While the stellar library consists of stars from the Milky Way, there is not a Milky Way specific trend in $[\text{Fe}/\text{H}]$ that we need to correct like we would for α elements (Tripicco & Bell 1995).

We also find that the color-metallicity relation differs between the Milky Way and M87, especially near the blue end ($g-z \lesssim 1.0$). We defer an in-depth examination of the physical cause of this difference to later work but we speculate that it might be age differences between the two GC populations. If the M87 GCs were younger than the Milky Way GCs, they would appear bluer at the same metallicities. We used simple stellar population (SSP) synthesis models to examine how age affects color at fixed metallicity (in this case, $[\text{Fe}/\text{H}] = -1.5$) and found that the metal-poor M87 GCs would have to be about 4 Gyr younger than the Milky Way GCs to explain the color difference. We also cannot rule out the

possible effects that α elements or the morphology of the blue horizontal branch have on the color.

4.2. Bimodality

Bimodality of GC systems has been the dominant paradigm in which extragalactic GC studies have been conducted over the past 30 yr. In this paper we defer quantitative analysis of the subpopulations of the GC system around M87 to a forthcoming paper on the topic. This is to more appropriately address the complexities around the topic that have been raised recently. Even with just the M87 system, a consensus has yet to be reached on the number of subpopulations that make up the system (e.g., Strader et al. 2011; Agnello et al. 2014; Oldham & Auger 2016). That said, there are still some things worth pointing out.

First, Cohen et al. (1998) detected bimodality in M87 only after excluding the metal-rich tail from their analysis. Usher et al. (2012) speculated that the lack of convincing proof for bimodality from Cohen et al. (1998) was a result of their typically bright targets. Since Cohen et al. (1998) we have become aware of the blue-tilt phenomenon as well as liminal objects like ultra-compact dwarfs that could contaminate populations of bright canonical GCs (e.g., Usher et al. 2012; Villaume et al. 2017a).

Second, we take advantage of obtaining color–metallicity relations using both the NGVS and ACSVCS data sets by converting both into metallicity and combining the data sets. The ACSVCS data probe the very inner region of the M87 GC system while the NGVS data extend further out. We see that the color-converted MDF is consistent with the spectroscopically determined MDF. Furthermore, bimodality can be seen visually from the MDFs, especially when only GCs within $R_{\text{gal}} < 10.5$ kpc are included.

The M87 system consists of a huge number of GCs that represent the culmination of a complex history. Previous analyses (e.g., Strader et al. 2011; Romanowsky et al. 2012) indicated that the GCs in the outer halo behave differently and are dominated by blue/metal-poor GCs. As mentioned previously, a paper specifically addressing the subpopulations and their characteristics will follow this paper.

Third, the Yonsei Evolutionary Population Synthesis (YEPS) models have been used to argue that most bimodal color distributions reflect a truly unimodal underlying metallicity distribution because of the inclusion of hot horizontal branch stars (Yoon et al. 2006). The approach of this group is different from the one typically taken, where spectroscopic observations of individual GCs are modeled with SPS models. Instead, the YEPS group transforms the color distributions of GC systems to metallicity distributions using synthetic color–metallicity relations generated from the YEPS models.

The results from the synthetic color–metallicity relation method (Yoon et al. 2006; Lee et al. 2019) and the direct spectroscopic modeling (e.g., Alves-Brito et al. 2011; Brodie et al. 2012; Usher et al. 2012) method continue to be at odds. The results we find in this work are consistent with other studies that have directly modeled spectroscopy of individual GCs. Beyond the final results there are few points of comparison between the two methods. However, we note that from our work with Milky Way GCs we know that the presence of hot horizontal branch stars affects our ability to measure accurate ages from integrated light but not metallicity (see Figure 15 in Conroy et al. 2018, for reference). We

therefore do not have a reason to doubt our metallicity measurements for the M87 GCs, even with the possible presence of GCs with prominent hot horizontal branches.

Fourth, it is important to note that our MDFs, both from the purely spectroscopic sample and the sample converting NGVS and ACSVCS photometry, differ significantly from the MDF computed from the Peng et al. (2006) relation. The peaks and widths of the distributions are different. These quantities are crucial for making quantitative comparisons to theoretical models of GC system formation, and thus, of galaxy formation. In recent years modern theoretical galaxy formation models have emerged with the E-MOSAICS simulations (Pfeffer et al. 2018) for Milky Way-type galaxies, and alternatively with Choksi et al. (2018) specifically trying to recreate the observed properties of the Virgo Cluster galaxies. These models take divergent approaches: E-MOSAICS adds models describing the formation and evolution of star clusters into the EAGLE galaxy formation simulations, while Choksi et al. (2018) uses semi-analytic models of merger histories. They also take different approaches to the role GC destruction plays in our understanding of $z \sim 0$ GC systems. Accuracy and credible uncertainties in the physical characteristics derived from observables are crucial for moving forward with constraining galaxy formation theories based on GCs.

4.3. Implications for GC and Galaxy Formation

We have derived a new galaxy luminosity–GC metallicity relation separately for the blue and red GCs in the Virgo galaxies included in Peng et al. (2006; Figure 12). The difference in our new color–metallicity relation is two-fold: the metal-poor GCs now correlate with galaxy luminosity less strongly than previously measured, and the metal-poor GCs are more metal-rich than what Peng et al. (2006) determined.

Larsen et al. (2001) were the first to assess the relationship between GC subpopulation metallicity and galaxy luminosity with a homogeneously acquired sample. Then Strader et al. (2004) combined elliptical galaxy data from a variety of sources (Kundu & Whitmore 2001a, 2001b; Larsen et al. 2001) with data from spiral galaxies (Harris 1996; Barmby et al. 2000) to look at just the metal-poor GCs. Most recently Peng et al. (2006) determined this relationship for the Virgo Cluster galaxies. Like Larsen et al. (2001), Peng et al. (2006) found shallower slopes for the metal-poor GCs relative to the metal-rich GCs. There is remarkable similarity between the slopes that Larsen et al. (2001), Strader et al. (2004), and Peng et al. (2006) found for the metal-poor GCs.

We already know that the difference between our relation and the relation from Peng et al. (2006) is due to the color–metallicity relation. What about the difference with Strader et al. (2004)? Strader et al. (2004) used the Barmby et al. (2000) color–metallicity relation based on a sample of M31 GCs. Barmby et al. (2000) noted that the M31 color–metallicity relation is similar to the Milky Way relation. This raises the likelihood that it is not an appropriate way to convert colors to metallicities for the ETGs included in the Strader et al. (2004) sample. The similarity in slopes between Strader et al. (2004) and Peng et al. (2006) might be an artifact of the similar source of their respective color–metallicity relations.

To explain the correlation between galaxy luminosity and blue GC metallicity Strader et al. (2005) and Brodie & Strader (2006) invoked the concept of “biasing,” also introduced in the context of Milky Way stellar halo assembly by Robertson et al. (2005).

In short, the progenitor satellites that now constitute the stellar halos of massive galaxies were more metal-rich, at fixed mass, than present-day satellites. In the light of the new, much weaker correlation, this needs to be reassessed. The new correlation could indicate that biasing is not as strong of an effect as once thought. Put another way, the new correlation suggests that metal-poor GCs formed irrespective of their host galaxies.

The change in metallicity intercept for the metal-poor GCs on this relation has implications for their formation epoch. Forbes et al. (2015) evolved the galaxy mass–GC metallicity relation through redshift to determine bulk ages of the GCs belonging to the galaxies in the SLUGGS survey (e.g., Usher et al. 2012). In their model, higher metallicities indicate younger ages and/or more massive hosts. The slopes of their metal-poor and metal-rich relations are not totally consistent with what we present in this work, but the intercepts are roughly similar. Following the logic of Forbes et al. (2015), the nearly constant slope we find for the metal-poor GCs as a function of galaxy luminosity indicates that the metal-poor GCs in the Virgo Cluster formed at nearly the same time. The correlation between the metal-rich GC [Fe/H] values and host galaxy luminosity indicates that the metal-rich GCs around the giant galaxies formed more recently than the metal-rich GCs around the dwarf galaxies. The increase in metallicity for the metal-poor GCs may also help ease the tension between simulated and observational results as discussed in the Introduction, if it indicates that the GCs formed in more massive satellites.

It is important to note the crucial underlying caveat of Figure 12—that the color–metallicity relation we developed for M87 is applicable to the other Virgo Cluster galaxies in the Peng et al. (2006) analysis. This is probably not a good assumption, particularly in light of the Powalka et al. (2016) results, which showed that color–color relations in the NGVS sample depend on environment, with colors on the whole becoming bluer with increased radial distance from M87 and that GCs > 200 kpc from M87 have color–color distributions similar to those of the Milky Way. Unfortunately, Powalka et al. (2016) also showed that mass is not the driving factor in these differences so we cannot make a simple correction to Figure 12. More detailed spectroscopy of lower-mass systems in the Virgo Cluster is ultimately needed.

5. Summary

1. We have fitted a spectroscopic sample of GCs around M87 with full-spectrum SPS models and obtained [Fe/H] for 177 GCs. We demonstrate that the metallicity values we derive are systematically higher metallicity than previous spectroscopic studies. We attribute this difference to the limitations of the previously used Worthey et al. (1994) SPS models and because the previously determined metallicity values were scaled to match the Milky Way GCs, which are, as a whole, lower in metallicity than the M87 GCs.
2. Using synthetic photometry from flux-calibrate stellar population models we determine a transformation between the NGVS and ACSVCS photometric systems: $(g-z)_{\text{ACSVCS}} = 1.123(g-z)_{\text{NGVS}} - 0.015$.
3. We derived new color–metallicity relations using both NGVS and ACSVCS $g-z$ colors. Our ACSVCS color–metallicity relation differs significantly for the blue GCs from the previously published color–metallicity relation

using the ACS filters. This is because we find the relation for the Milky Way GCs to be significantly different from the relation for the M87 GCs. We discuss the necessary age difference needed to explain this result, but previous work in colors of Virgo Cluster GCs suggested that there is some environmental effect on chemical abundance patterns.

4. While we advocate that color–metallicity relations be confirmed with spectroscopic follow-up for individual galaxies, we assume that in this respect the Virgo cluster galaxies are similar to one another and as a result we find a shallower galaxy luminosity–GC metallicity relation for the blue GCs than previous studies. This could either indicate that progenitor satellites were less massive than previously thought, or the properties of metal-poor GCs are not as dependent as their present-day host galaxy as metal-rich GCs.

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