NONLINEAR COLOR–METALLICITY RELATIONS OF GLOBULAR CLUSTERS. II.
A TEST ON THE NONLINEARITY SCENARIO FOR COLOR BIMODALITY
USING THE u-BAND COLORS: THE CASE OF M87 (NGC 4486)

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ABSTRACT

The optical color distributions of globular clusters (GCs) in most large elliptical galaxies are bimodal. Based on the assumed linear relationship between GC colors and their metallicities, the bimodality has been taken as evidence of two GC subsystems with different metallicities in each galaxy and has led to a number of theories in the context of galaxy formation. More recent observations and modeling of GCs, however, suggest that the color–metallicity relations (CMRs) are inflected, and thus colors likely trace metallicities in a nonlinear manner. The nonlinearity could produce bimodal color distributions from a broad underlying metallicity spread, even if it is unimodal. Despite the far-reaching implications, whether CMRs are nonlinear and whether the nonlinearity indeed causes the color bimodality are still open questions. Given that the spectroscopic refinement of CMRs is still very challenging, we here propose a new photometric technique to probe the possible nonlinear nature of CMRs. In essence, a color distribution of GCs is a “projected” distribution of their metallicities. Since the form of CMRs hinges on which color is used, the shape of color distributions varies depending significantly on the colors. Among other optical colors, the u-band related colors (e.g., u − g and u − z) are theoretically predicted to exhibit significantly less inflected CMRs than other preferred CMRs (e.g., for g − z). As a case study, we performed the Hubble Space Telescope (HST)/WFPC2 archival u-band photometry for the M87 (NGC 4486) GC system with confirmed color bimodality. We show that the u-band color distributions are significantly different from that of g − z and consistent with our model predictions. With more u-band measurements, this method will support or rule out the nonlinear CMR scenario for the origin of GC color bimodality with high confidence. The HST/WFPC3 observations in F336W for nearby large elliptical galaxies are highly anticipated in this regard.

Key words: galaxies: clusters: general – galaxies: formation – galaxies: individual (M49, M60, M87) – stars: horizontal-branch

Online-only material: color figures, machine-readable table

1. INTRODUCTION

Globular clusters (GCs) are among the oldest stellar systems in the observable universe and are always present in large galaxies. There is substantial evidence that GCs are the remnants of star formation events in galaxies and are linked to the star formation, chemical enrichment, and assembly histories of their parent galaxies. Due to their bright and compact nature, GCs are detected out to great distances. Moreover, each GC around a galaxy has a small internal dispersion in age and abundance, and thus light from GCs is relatively easier to interpret than integrated light from complex stellar populations of galaxies. Such unique properties make GCs ideal objects for constraining the formation and evolution of their host galaxies (see West et al. 2004 and Brodie & Strader 2006 for reviews).

One of the most significant discoveries in the field of extragalactic GCs over the past few decades is the bimodal optical color distributions (e.g., C − T1, V − I, and g − z) of GC systems. The first recognition and statistical study of GC color bimodality was done by Zepf & Ashman (1993), and subsequent observations have found that this feature is ubiquitous in a majority of massive galaxies (Ostrov et al. 1993; Whitmore et al. 1995; Lee et al. 1998; Gebhardt & Kissler-Patig 1999; Harris 2001; Kundu & Whitmore 2001; Larsen et al. 2001; Peng et al. 2004a, 2004b, 2006; Harris et al. 2006; Jordan et al. 2009; Sinnott et al. 2010; Liu et al. 2011).

Because GCs in the Milky Way and other galaxies are usually older than 10 Gyr and age does not strongly affect broadband colors of GCs this old, their colors are primarily governed by metallicity. Empirical relations between the most often used broadband color, V − I, and [Fe/H] have been traditionally fit with a linear function. Using the more metallicity-sensitive colors C − T1 or C − R, Harris & Harris (2002) and Cohen et al. (2003) found a mildly quadratic or broken linear relation between color and [Fe/H]. With the linear or mildly curved color-to-metallicity conversion, the bimodality observed in GC color distributions has been widely interpreted as bimodal metallicity distributions and hence taken as evidence of two distinct GC subsystems. The physical origin of two GC subgroups within a single galaxy and its implications in the context of galaxy formation have been the topics of much interest (e.g., Ashman & Zepf 1992; Forbes et al. 1997; Côté et al. 1998; Lee et al. 2010).

The key assumption behind the interpretation that bimodal color corresponds to bimodal metallicity is the linear...
relationship between intrinsic metallicities and, their proxies, colors. Indeed, simple linear conversion of photometric colors to metallicities is a reasonable first-order assumption for obtaining the mean values of metallicities for GC systems. But for investigating the detailed structure of GC metallicity distributions, including possible two-metallicity groups, the form of the color–metallicity relation (CMR) must be known to higher order. In general, the slope of the dependence of a given photometric color on the logarithmic metallicity [Fe/H] will change as a function of metallicity. It has been known for decades that the color of the giant branch in Galactic GCs is a nonlinear function of [Fe/H] (e.g., Michel & Smith 1984). Recent observations (Peng et al. 2006; Lee et al. 2008) and theories (Lee et al. 2002; Yoon et al. 2006; Cantiello & Blakeslee 2007) have found departures from linearity for integrated GC colors as a function of [Fe/H]. If the bona fide shape of CMRs is nonlinear, what have been thought to be metallicity distribution functions of GC systems may deviate significantly from the true distributions. Therefore knowing their precise CMR forms will be crucial to our understanding of the formation of GC systems and their host galaxies.

In this paper, given that the direct spectroscopic refinement of CMRs is still very challenging, we propose a new photometric tool to probe the nonlinear nature of CMRs: the photometric color distributions involving the u bandpass (or ”u-band color distributions”). Section 2 recapitulates the nonlinear-CMR scenario for the origin of GC color bimodality as proposed in Yoon et al. (2006, hereafter Paper I). Section 3 presents a case study of the M87 (NGC 4486) GC system with confirmed color bimodality and shows that the Hubble Space Telescope (HST)/WFC2 F336W-u bandpass (or ”u-band color distributions”). The modeled and observed CMRs for g-z (upper right quadrant), u-z (lower left), and u-g (lower right) are displayed along with the color–magnitude diagrams generated from the synthetic log $T_\text{eff}$ versus log $L/L_\odot$ diagrams in the upper left quadrant. Table 1 summarizes the references to the observed data used in the CMRs. Tables 2–4 give the theoretical g-z, u-z, and u-g CMRs, respectively, based on the YEPS model.

This section focuses on the g-z CMR. An inspection of the observed g-z CMR suggests that it follows an inverted S-shaped “wavy” curve with a quasi-inflation point at $g-z \simeq 1.3$. The YEPS model suggests that the observed wavy feature in the g-z CMR is a consequence of two complementary effects. (1) The integrated color of the stars on the main-sequence and red giant branch stages (denoted by red isochrones in color–magnitude diagrams on the right) is a nonlinear function of metallicity at given ages. As a result, the CMR (dashed line) features a mild departure from linearity at lower metallicity. (2) Standard stellar evolutionary theories predict nonlinear dependence of the mean color of horizontal-branch (HB) stars on metallicity (e.g., Lee & Demarque 1990; Yi et al. 1997). The accompanying color–magnitude diagrams on the right illustrate such an effect of metallicity on the systematic HB color variation. The color of the HB changes at a brisk pace between [Fe/H] = -0.5 and -0.9 where the HB just departs from the red-clump position. The HB contribution further strengthens the departure from linearity for the g-z CMR.

The nonlinear-CMR scenario gives a simple and cohesive explanation for the key observations, including (1) the overall shape of color histograms, (2) the number ratio of blue and red GCs as a function of host galaxy luminosity, and (3) the peak colors of both blue and red GCs as a function of host luminosity.

The observational and theoretical evidence for and against the nonlinearity of the CMRs, as well as the alternative hypothesis of bimodality in the intrinsic metallicity distributions, has been addressed in detail by Blakeslee et al. (2010) and Yoon et al. (2011, hereafter Paper III). We refer the reader to those works for further discussion.

Figures 1 and 2 convey the essence of the Paper I explanation. Figure 1 shows the synthetic color–magnitude diagrams for individual stars of the model GCs and compares the resulting theoretical CMRs with observations. The stellar population simulations are based on the Yonsei Evolutionary Population Synthesis (YEPS) model (Chung et al. 2011; S.-J. Yoon et al. 2011, in preparation). The upper left quadrant presents the synthetic log $T_\text{eff}$ versus log $L/L_\odot$ diagrams for 14 Gyr old GCs with selected [Fe/H]’s, at which the departure of CMRs from linearity is most prominent. The selected [Fe/H]’s are marked by horizontal arrows in the CMRs in the other three quadrants. The modeled and observed CMRs for g-z (upper right quadrant), u-z (lower left), and u-g (lower right) are displayed along with the color–magnitude diagrams generated from the synthetic log $T_\text{eff}$ versus log $L/L_\odot$ diagrams in the upper left quadrant. Table 1 summarizes the references to the observed data used in the CMRs. Tables 2–4 give the theoretical g-z, u-z, and u-g CMRs, respectively, based on the YEPS model.

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The possibility of inflected, nonlinear CMRs has been extensively investigated on both observational and theoretical grounds. Peng et al. (2006) presented an empirical relation between color and metallicity using observed g-z colors and spectroscopic measurements of [Fe/H] for GCs in the Milky Way, M49, and M87. The observed relation is tight enough to show a notable departure from linearity. The relation between [Fe/H] and g-z is steep for [Fe/H] < -0.8, shallow up to [Fe/H] ≃ -0.5, and then steep again at higher metallicites. They proposed a piecewise linear relation broken at $g-z \simeq 1.05$ or [Fe/H] ≃ -0.8. Independently, Paper I presented a theoretical metallicity–color relationship that has a significant inflection and reproduces well the observed g-z CMR by Peng et al. (2006). The nonlinear nature of the relation between intrinsic metallicity and its proxy, colors, may hold the key to understanding the color bimodality phenomenon. Paper I showed that the wavy feature projects equidistant metallicity intervals near the quasi-inflation point (i.e., the most metallicity-sensitive point) onto larger color intervals, and thus can produce bimodal GC color distributions from a broad underlying [Fe/H] distribution, even if it is unimodal. The nonlinear-CMR scenario gives a simple and cohesive explanation for the key observations, including (1) the overall shape of color histograms, (2) the number ratio of blue and red GCs as a function of host galaxy luminosity, and (3) the peak colors of both blue and red GCs as a function of host luminosity.
As a combined effect of (1) the main-sequence and red giant branch stars and (2) the HB stars, the $g - z$ color becomes several times more sensitive to metallicity between $[\text{Fe/H}] \approx -0.5$ and $-0.9$, resulting in a quasi-inflection point at $[\text{Fe/H}] \approx -0.7$. Note that, because the range of the rapid change in $g - z$ is as small as $\sim 0.5$ in $[\text{Fe/H}]$, the wavy feature would not be discernible in models with an $[\text{Fe/H}]$ grid spacing larger than $\sim 0.3$.

Deferring the examination on the $u - z$ and $u - g$ CMRs until the next section, we demonstrate in Figure 2 the effect of the nonlinear CMRs on observed color distributions of GCs. Our simulations target the M87 GC system, which exhibits a clear bimodality in the $HST$/Advanced Camera for Survey (ACS) $g - z$ distribution (Peng et al. 2006) and is one of few galaxies with deep $HST$ $u$-band photometry (see Section 3 below). The first column of Figure 2 shows how the inflected (or wavy) $g - z$ CMR causes bimodality in the $g - z$ color distribution. The nonlinear feature in the CMR (top row) has the effect of projecting the equidistant $[\text{Fe/H}]$ intervals onto broader $g - z$ intervals, causing scarcity at the quasi-inflection point on the CMR. As an aid to visualizing the simulated $g - z$ distribution, we plot the color versus magnitude diagram in the second row. The divide between two vertical bands of GCs is immediately visible. The resulting $g - z$ histograms (third row) show clear bimodality: the scarcity near the quasi-inflection point is reflected as a clear dip. The agreement between the simulated (third row) and observed (bottom row) $g - z$ distributions for the M87 GC system is remarkable, without having to invoke a bimodal metallicity spread.
Figure 2. Multiband \((u, g, \text{ and } z)\) observation of GCs in M87 and Monte Carlo simulations for their color distributions. Top row: same as the CMRs in Figure 1. The metallicity spread of \(10^6\) model GCs is shown along the \(y\)-axis, for which a simple Gaussian distribution is assumed \((\langle [\text{Fe/H}] \rangle = -0.5 \text{ dex and } \sigma ([\text{Fe/H}]) = 0.6)). The best-fit age to reproduce the morphologies of \(g - z\), \(u - z\), and \(u - g\) color histograms simultaneously is 13.9 Gyr. Second row: the left, middle, and right columns represent the color–magnitude diagrams of 2000 randomly selected model GCs for the \(g - z\), \(u - z\), and \(u - g\) colors, respectively. The colors are transformed from \([\text{Fe/H}]\)'s by using the theoretical relation shown in the top row. For the integrated \(u\)-band absolute mag, \(M_u\), a Gaussian luminosity distribution \((\langle M_u \rangle = 25.2, \text{ distance modulus} = 31.02, \text{ and } \sigma (M_u) = 1.15)\) is assumed according to the observation. Observational uncertainties as a function of \(M_u\) shown by error bars are taken into account in the simulations. Third row: the left, middle, and right columns represent the color distributions of \(10^6\) modeled GCs for the \(g - z\), \(u - z\), and \(u - g\) colors, respectively. Bottom row: same as the third row, but the observed color histograms for the M87 GC system (see Figure 3). The 591 GCs were used that have \(u\), \(g\), and \(z\) measurements in common, and the sample is \(u\)-band limited. Solid lines are smoothed histograms with Gaussian kernels of \(\sigma (g - z) = 0.05\), \(\sigma (u - z) = 0.10\), and \(\sigma (u - g) = 0.15\), respectively.

(A color version of this figure is available in the online journal.)
3. A CRITICAL TEST FOR THE NONLINEARITY SCENARIO USING u-BAND COLORS

3.1. Conversion from Metallicities to Colors

Despite far-reaching implications of the nonlinear-CMR scenario for the origin of GC color bimodality (Paper I), whether CMRs are nonlinear and whether the nonlinearity indeed causes the color bimodality are still open questions. Even the best samples currently available for the empirical color–metallicity calibrations are still relatively small and sparsely populated at the high-metallicity end, and exhibit significant observational scatter (e.g., Peng et al. 2006; Lee et al. 2008; Beasley et al. 2008).

The full model data are available at http://web.yonsei.ac.kr/cosmic/data/YEPS.htm.
Given that the more stringent spectroscopic refinement of CMRs is still very challenging, we propose the \( u \)-band color distributions as a new tool to probe the nonlinear nature of CMRs. The nonlinearity issue drew our attention to the simple, basic fact that, in essence, a color spread of GCs is a "projected" distribution of their metallicities. Since the form of CMRs hinges on which color is used, the shape of color distribution varies depending significantly on the colors. Hence a comparative analysis of the GC color distributions for different colors will offer a powerful tool for probing the presence of the nonlinear projection effect at work. We have explored various combinations consisting of the commonly used broadband filters and found that among other optical colors, the \( u \)-band related colors (e.g., \( u - g \) and \( u - z \)) are theoretically predicted to exhibit the most distinctive CMRs from other preferred CMRs (e.g., for \( g - z \)).

In order to examine the characteristic of the \( u \)-band colors, we turn back to Figure 1. The lower left and lower right quadrants of Figure 1 show the \( u - z \) and \( u - g \) CMRs, respectively. For a given age, the CMRs for the \( u \)-band colors are substantially less inflected than the \( g - z \) CMR. This is because the integrated \( u \)-band colors of main-sequence and red giant branch stars are smoother functions of metallicity compared to \( g - z \). In addition, the \( u \)-band colors are less sensitive to the temperature (i.e., log \( T_\text{eff} \)) variation of HBs, which is due to the fact that the blueing effect of the optical spectra with increasing HB temperature is held back by the Balmer discontinuity where the \( u \) band is located (Yi et al. 2004). This is evidenced by individual HB stars in the color–magnitude diagrams (blue dots in the small panels on the right) of synthetic GCs with different metallicity. Such properties of the \( u \) band make the \( u - z \) and \( u - g \) colors good metallicity indicators for a wide range of age, and the \( u \)-band color distributions are expected to be significantly different from distributions of other optical colors such as \( g - z \), \( V - I \), and \( C - T_\text{eff} \). A comparison shows that \( u - g \) is less inflected than \( u - z \), and, as a result, the degree of nonlinearity is in order of \( g - z \), \( u - z \), and \( u - g \).

As a case study, we have selected M87 (NGC 4486), the central cD galaxy in the Virgo galaxy cluster. The M87 GC system is not only with confirmed color bimodality, but also among few elliptical galaxies with deep \( u \)-band observations. We have downloaded WFPC2 F336W (hereafter \( u \)) images from the HST archive. The total exposure time is 28.8 ks. These data were used by Jordán et al. (2002) for investigating the relative age difference between blue and red GCs in M87. Our data reduction and photometry procedures are essentially identical to those of Jordán et al. (2002). In summary, we processed the WFPC2
images with standard pipeline and measured the brightness of each point source using DAOPHOT with aperture radii of 2 and 3 pixels for the WF and PC chips, respectively. Aperture corrections were derived and applied to a $0.5$ radius using bright GC candidates, and charge transfer efficiency corrections were applied following Whitmore et al. (1999). We then applied an additional correction of 0.1 mag to correct to infinite aperture (Holtzman et al. 1995), and finally converted instrumental mags to the standard AB mag system. Our $w$-band catalog was matched with ACS/WFC $g$- and $z$-band photometry of Jordán et al. (2009) after placing both the WFC2 and the ACS catalogs on a common coordinate system. A matching radius of $1''$ was used. Sources were visually inspected to ensure that the matching was done properly. Jordán et al. (2009) selected bona fide GCs with their mags, $g-z$ colors, and sizes. We further employed $u$-band color cuts ($u-g < 0.8$) to filter out contaminating sources, especially background star-forming galaxies. We compared our observed luminosity functions to those presented in Jordán et al. (2002) and did not find any noticeable difference.

Figure 3 displays the observed GCs in M87 on the color–magnitude diagrams (top panels) and on the color–color diagrams (bottom panels) along with their color distributions. The ID, R.A., decl., $u$, $g$, and $z$-band mags, and their observational errors of $\sim 800$ M87 GCs are given in Table 5. In this study, we consider $\sim 600$ GCs (with $u \leq 0.2$ mag) that have reliable $u$, $g$, and $z$ photometry in common, and the sample is $u$-band limited. In the color–magnitude diagrams (top panels), the divide between two vertical bands of GCs is immediately visible for $g-z$, whereas the division appears less clear for $u-z$ and $u-g$. In the color–color diagrams (bottom panels), as all the three colors get redder with increasing metallicity, they are directly proportional to one another. The color–color relations are thus basically the metallicity sequences. The red loci represent our model predictions for coeval (13.9 Gyr) GCs from the metal-poorest ([Fe/H] = $-2.5$) to the metal-richest ([Fe/H] = 0.5) GCs, respectively. The red crosses on each model line mark the uniform [Fe/H] intervals ($\Delta$[Fe/H] = $0.2$ dex). The larger color intervals at the midpoint of each color–color relation are consistent with the observed lower density of GCs at the intermediate metallicity. Despite the agreement between the observed and modeled color–color relations, there are slight offsets, which we attribute to the fact that current population simulations are still incomplete in terms of the stellar evolutionary tracks and/or the atmospheric libraries. The scatter around the color–color relations is mainly due to the observational errors, although it may be partially due to possible spreads in the parameters of GCs, such as age and $[u/Fe]$. The gray histograms in bottom panels are the color distributions, which are used repeatedly in Figures 2, 4, and 5.
Upper: the color–magnitude diagrams for the GC system of M87. The left, middle, and right panels show the \(g - z\), \(u - z\), and \(u - g\) distributions, respectively. The \(g\) (ABMAG) and \(z\) (ABMAG) mags for GC candidates are from the ACS GC catalog (Jordán et al. 2009). Using the HST/WFPC2 archival images, we measured \(u\)-band mags (F336W, ABMAG) for the M87 GC candidates listed in the ACS GC catalog. A color cut \((u - g < 0.8)\) was employed to filter out contaminating sources, presumably star-forming background galaxies. Lower: the color–color diagrams and the projected color histograms for the GC system of M87. In this study, we used GCs that have \(u\), \(g\), and \(z\) measurements in common, and the sample is \(u\)-band limited. The \(\sim 800\) GC candidates are listed in Table 5. Black dots in each panel are the selected \(\sim 600\) GCs \((\sigma_{u} < 0.2\) mag). Red solid lines represent our model prediction for 13.9 Gyr GCs (Tables 2–4) from the metal-poorest \([\text{Fe}/H] = -2.5\), top left point) to the metal-richest \([\text{Fe}/H] = 0.5\), bottom right point). The red crosses on each model line mark the uniform \([\text{Fe}/H]\) intervals \((\Delta[\text{Fe}/H] = 0.2\) dex).

(A color version of this figure is available in the online journal.)

### Table 5

| GC ID | R.A. (J2000) | Decl. (J2000) | \(u_{o}\) (WFPC3 F336W) | \(u \text{ error}\) | \(g_{o}\) (ACS/WFC F475W) | \(g \text{ error}\) | \(z_{o}\) (ACS/WFC F850LP) | \(z \text{ error}\) |
|-------|---------------|---------------|--------------------------|-----------------|--------------------------|-----------------|--------------------------|-----------------|
| 1     | 187.7056427   | 12.3909702    | 25.375                   | 0.212           | 23.275                   | 0.083           | 22.668                   | 0.090           |
| 2     | 187.7065999   | 12.3914337    | 25.829                   | 0.275           | 23.817                   | 0.108           | 22.580                   | 0.119           |
| 3     | 187.7055817   | 12.3919382    | 24.102                   | 0.040           | 22.122                   | 0.027           | 20.749                   | 0.037           |
| 4     | 187.7067566   | 12.3914499    | 26.307                   | 0.230           | 24.064                   | 0.112           | 22.408                   | 0.110           |
| 5     | 187.7069092   | 12.3912528    | 25.570                   | 0.115           | 23.810                   | 0.093           | 22.259                   | 0.078           |
| 6     | 187.7063293   | 12.3921633    | 25.516                   | 0.142           | 23.002                   | 0.031           | 21.521                   | 0.042           |
| 7     | 187.7062683   | 12.3902464    | 25.836                   | 0.202           | 23.370                   | 0.043           | 21.957                   | 0.046           |
| 8     | 187.7059631   | 12.3898511    | 24.170                   | 0.046           | 21.829                   | 0.022           | 20.451                   | 0.013           |
| 9     | 187.7071381   | 12.3918767    | 23.499                   | 0.021           | 21.169                   | 0.015           | 19.779                   | 0.017           |
| 10    | 187.7046356   | 12.3907633    | 26.113                   | 0.226           | 24.061                   | 0.100           | 22.583                   | 0.057           |

Notes. \(\text{a}\) The \(g\)- and \(z\)-band data are obtained from Jordán et al. (2009).

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

In Figure 2, the observed \(u - z\) and \(u - g\) color distributions of M87 GCs are shown in the bottom panels of the second and third columns, respectively. The observed \(u\)-band color distributions are systematically different from the \(g - z\) distribution (first column), in that the prominence of bimodality found in \(g - z\) is weakened in \(u - z\) and diminished substantially in \(u - g\). Although this is readily expected from the difference among the model CMRs in the degree of nonlinearity, one may wonder about the role of observational uncertainties in weakening bimodality. Table 6 shows that the typical photometric errors of
both $u-z$ and $u-g$ are, respectively, 2.3 and 2.2 times larger than that of $g-z$, but at the same time the ranges spanned by the colors are $\Delta(g-z), \Delta(u-z), \Delta(u-g)) = (1.1 \text{ mag}, 2.7 \text{ mag}, 2.1 \text{ mag})$, that is, the baselines of $u-z$ and $u-g$ are, respectively, 2.5 and 1.9 times longer than that of $g-z$. As a result, the relative sizes of error bars are calculated to be $(g-z: u-z: u-g) = (1.0:0.9:1.2)$. In a relative sense, the errors in the three colors are quite comparable to one another. Moreover, the $u-z$ color, which has the smallest relative errors, still shows weakened bimodality in the color distribution. It is, therefore, not likely that bimodality is simply blurred by larger observational errors in the $u$ band. In the third row, the observational uncertainties as a function of mag are fully taken into account in the simulated color distributions. The parameters that match up the morphologies of $g-z$, $u-z$, and $u-g$ color histograms simultaneously are 13.9 Gyr, $-0.5$ dex, and 0.6 dex for age, mean [Fe/H], and $\sigma$([Fe/H]), respectively. Note that that the mean colors of modeled GCs are redder than the observation by 0.1–0.2 mag. Our stellar population models show that, for given input parameters, the absolute quantities of output are rather subject to the choice of stellar evolutionary tracts and model flux libraries, and the different choices can result in up to $\sim0.2$ mag variation in the

Figure 4. $g-z$, $u-z$, and $u-g$ color distributions and their inferred metallicity distributions for the GC system of M87. Top row: same as the bottom row of Figure 2. Middle row: same as the top row of Figure 2, but the dotted lines represent the least-squares fits to the observational data points which are not shown here for clarity. Bottom row: the left, middle, and right panels show GC metallicity distributions obtained from the $g-z$, $u-z$, and $u-g$ color distributions, respectively. The metallicity distributions are derived from the smoothed histograms in the top row via the nonlinear transformations (gray histograms with solid lines) and via the linear transformation (open histograms with dotted lines).
Figure 5. Same as Figure 4, but the observed histograms are expressed by a sum of two unimodal distributions. Top row: same as the top row of Figure 4, but the histograms are expressed by two (i.e., blue and red) Gaussian distributions based on the KMM analysis. The blue, red, and black lines represent the blue, red, and total GCs, with the peak colors and number fractions of blue and red GCs being [(0.98, 1.40), (50%, 50%)] for $g-z$, [(2.50, 3.48), (53%, 47%)] for $u-z$, and [(1.53, 2.10), (59%, 41%)] for $u-g$, respectively. Middle row: same as the middle row in Figure 4, but without the observational data or the linear least-squares fits. Bottom row: same as Figure 4, but the GC metallicity distributions are derived from the blue and red Gaussian distributions in the top row through the color-to-metallicity transformations in the middle row. The blue, red, and black lines represent the blue, red, and total GCs.

(A color version of this figure is available in the online journal.)

$g-z$, $u-z$, and $u-g$ colors. Hence, we put more weight on the relative color values of modeled GCs, i.e., the blue-to-red number ratios and the overall morphologies of the simulated color histograms.

We emphasize that, in the conventional view where GC colors linearly trace GC metallicities, there is no reason for the shape of color histograms to vary significantly with the colors in use unless the observational uncertainties of different colors are incomparable. Two distinct GC subpopulations would manifest themselves even in different colors more or less in the same way. In contrast, in the context of the nonlinear CMRs, the variation in the histogram morphology for different colors is readily understood if the shape of the CMRs depends significantly on the choice of colors as evident from the top panels of Figure 2. Indeed, there is reasonable agreement between the theoretically predicted (third row) and observed (bottom) $u-z$ and $u-g$ color distributions for the case of M87 GCs.

3.2. Inverse Conversion from Colors to Metallicities

The above experiment suggests that a color distribution of a GC system does not directly expose its intrinsic metallicity...
This occurrence indicates that the nonlinear CMR projection of metallicity for M87 GCs are also used in Figure 4. The three ob-
uixon distributions of the M87 GC system. The middle row shows that distributions derived based on the conventional are remarkably consistent with one another in terms of their metallicity distributions are affected by the observational uncer-
voni, the broadness and the exact shape of wings of the inferred
r content of current models will be amplified by inverse transformation, giving metallicity distributions in error. Nev-
ertheless, a careful comparative analysis of the GC metallicity distributions that are independently obtained from different color histograms will shed some light on the color–metallicity nonlinearity hypothesis.

The inverse transformations are applied again to the M87 GC system. The top panels of Figure 4 are identical to the bottom panels of Figure 2 and show the observed $g - z$, $u - z$, and $u - g$ distributions of the M87 GC system. The middle row shows that the $u$-band colors have significantly less inflected, “smoother” CMRs than $g - z$. Therefore, obtaining metallicity distributions from $u$-band color distributions via the $u$-band CMRs should be more straightforward than the case of $g - z$. The bottom row of Figure 4 presents the GC metallicity histograms derived from $g - z$, $u - z$, and $u - g$ colors that are based on the inflected color-to-metallicity conversions shown in the middle row. The best-fit parameters obtained in Figure 2 for the age and mean metallicity for M87 GCs are also used in Figure 4. The three ob-
erved color histograms with different morphologies (top row) are transformed into metallicity distributions (bottom row) that have a strong metal-rich peak with a metal-poor tail. Although the broadness and the exact shape of wings of the inferred metallicity distributions are affected by the observational uncertainties in the colors of interest, the three metallicity histograms are remarkably consistent with one another in terms of their overall shape and their peak positions. In contrast, the three distributions derived based on the conventional linear color-to-metallicity conversions (dotted lines in the middle row) are just replicas of their color histograms (dotted histograms in the bottom row), and thus do not agree with one another. We wish to emphasize that, under the nonlinear-CMR assumption, the typical shape of the metallicity distributions is obtained invariably from different colors, i.e., $g - z$, $u - z$, and $u - g$ for M87 GCs. This occurrence indicates that the nonlinear CMR projection effect is at work for the colors examined in this study.

Figure 5 presents another experiment of the inverse trans-
formations. Following the conventional interpretations, the ob-
erved color distributions (top row) are divided into two distinct subgroups and described as the sum (black lines) of two Gaussian distributions (blue and red lines). The bottom row gives the de-projected metallicity distributions of blue and red GCs that are based on the inflected color-to-metallicity conversions shown in the middle row. As one may expect from the result in Figure 4, the three different combinations of two Gaussian distributions (top row) are all transformed into metallicity distributions that are similar to one another (bottom row). Still, it may be possible that two subgroups do dwell even in a single unimodal metallicity distribution. However, it is interesting that the typical shape, characterized by a sharp peak with a metal-poor tail, of the metallicity distributions seems to coincide with those produced by galaxy chemical evolution models assuming a virtually continuous chemical evolution through many successive rounds of star formation. Perhaps more importantly, the typical shape is also similar to that of metallicity distributions for resolved field stars in nearby elliptical galaxies (e.g., Bird et al. 2010 for the M87 field-star metallicity distribution). The implications of the typical shape of the inferred GC metallicity distributions and its similarity to those from chemical evolution models and field-star observations are very important and suffi-
ciently involved that we will discuss the issue in a separate paper (Paper III).

4. DISCUSSION AND CONCLUSION

In order to explore to what extent nonlinear metallicity-to-
color transformations for GCs may be responsible for turning a unimodal metallicity distribution into bimodal color distributions, we have proposed a $u$-band color technique. We showed that the addition of the $u$-band photometry to the existing $g$ and $z$ data has the potential of judging which CMRs are close to the true forms. Using the $HST$ photometry, we demonstrated that the $g - z$, $u - z$, $u - g$ color distributions for the rich GC system of M87 differ significantly, and all appear to be reasonably consistent with mapping from a single unimodal distribution of metallicity. The results of our experiments on the M87 GCs in Sections 2 and 3 strengthen the claim that the each CMR has a wavy form instead of a linear one. Obviously, the next step is to carry out the test on the nonlinear-CMR scenario using more GC systems. In this section, we discuss the theoretically predicted $u$-band color distributions of GCs in massive elliptical galaxies, anticipating that the $u$-band observations (e.g., using the $HST$/WFC3 F336W) of nearby massive elliptical galaxies will be available in the near future.

Our prediction of the $u$-band color distributions is made based on the existing observational data on the $g - z$ distributions using our theoretical CMRs. Our simulations target two nearby giant elliptical galaxies, M49 and M60 in the Virgo galaxy cluster. The galaxies meet the following criteria: (1) the number of observed GCs is relatively large, (2) deep $g$ and $z$ photometry exists in the $HST$ archive, and (3) their observed $g - z$ color distributions show clear bimodality. The two galaxies have ACS $g$ and $z$ photometry for more than 700 GCs (Jordán et al. 2009) and show strong $g - z$ color bimodality (Peng et al. 2006). We note that the galaxies may have younger populations of GCs, but with the addition of the $u$-band measurements, identification of these younger GCs will be trivial (Hempel & Kissler-Patig 2004; Yi et al. 2004; Kaviraj et al. 2005), thus allowing us to use only the old GCs.

Figure 6 illustrates how the $u$-band observations can be used to improve our understanding of CMRs and metallicity distributions of GC systems. We utilize existing $g$ and $z$ photometry for the galaxies (leftmost column). Note that, with the $u$-band limited samples, the red GCs in $g - z$ would be more subject to going under the detection limit, but the typical shape of the inferred metallicity distributions would persist as

### Table 6

| Mag Bins | Number of GCs | $g - z$ Error | $u - z$ Error | $u - g$ Error |
|----------|---------------|---------------|---------------|---------------|
| $u_0 \leq 23.0$ | 20 | 0.019 | 0.018 | 0.024 |
| $23.0 < u_0 \leq 24.0$ | 87 | 0.022 | 0.026 | 0.028 |
| $24.0 < u_0 \leq 25.0$ | 172 | 0.030 | 0.054 | 0.054 |
| $25.0 < u_0 \leq 26.0$ | 247 | 0.043 | 0.111 | 0.110 |
| $u_0 > 26.0$ | 65 | 0.058 | 0.175 | 0.175 |
| Entire sample | 591 | 0.035 | 0.080 | 0.078 |
expected from the result of the M87 GC system. The right two columns show the predicted $u-g$ distributions under two different assumptions: the CASE 1 for the conventional linear CMRs (middle column); the CASE 2 for the nonlinear CMRs (rightmost column). The observed $g-z$ distribution of each GC system was first translated into the [Fe/H] domain (the vertical metallicity histograms along the y-axis) via the linear (CASE 1) and nonlinear (CASE 2) $g-z$ vs. [Fe/H] relations. The hashed metallicity histograms (CASE 1) and the empty metallicity histograms with thick solid lines (CASE 2) are then converted to the $u-g$ distributions (the horizontal metallicity histograms along the x-axis) via the linear (CASE 1) and nonlinear (CASE 2) [Fe/H]-to-($u-g$) conversions.

A given intrinsic metallicity distribution of GCs should be manifested by different color distributions depending on the passbands in use. We have shown the power of $u$ band in discriminating between the two competing scenarios for the form of CMRs. By the projection effect, any feature on CMRs is manifested on the color domain. Hence, under the assumption of the nonlinear CMRs, the $u$-band color distributions are significantly different and readily distinguishable from those under the assumption of the conventional linear CMRs. With more data, this method will support or rule out the nonlinear-CMR scenario for GC color bimodality with high confidence. Further $u$-band measurements for GC systems with color bimodality are clearly needed, and the HST/WFC3 observations in F336W for nearby large elliptical galaxies are highly anticipated in this regard. It is also noteworthy that another path we can take is to extend the photometry to IR passbands (e.g., Hempel et al. 2007; Kundu & Zept 2007; Spitler et al. 2008; Chies-Santos et al. 2010, 2011b, 2011a), where the contribution from the HB is just as systematic as in the $u$ passband. Interestingly, the most recent NIR/optical photometric study (Chies-Santos et al. 2010) finds that the GC bimodality of 14 early-type galaxies behaves systematically in that it becomes less evident in $g-K_s$ and even weaker in $z-K_s$ when compared to $g-z$. If the nonlinearity of CMRs is found to be favored by future multiband observations involving the $u$ and IR bands, it will change much of the current thought on the GC color bimodality as well as the formation of GCs and their host galaxies.

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