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THE RELATIVE AGES OF THE GLOBULAR CLUSTER SUBPOPULATIONS IN M87[1]

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ABSTRACT

Relative ages for the globular cluster (GC) subpopulations in the Virgo giant elliptical galaxy M87 (NGC 4486) have been determined from Strömgren photometry obtained with the Wide Field Planetary Camera 2 on board the *Hubble Space Telescope*. Using a variety of population synthesis models, and assuming the GC mass at the turnover of the luminosity function is the same for both subpopulations, differential ages have been determined from the observed magnitudes at the turnover of the globular cluster luminosity function and from the mean color of each subpopulation. We measure an age difference between the two subpopulations of 0.2 ± 1.5 (systematic) $\pm$ 2 (random) Gyr, in the sense that the blue GCs are formally older. Thus, to within our measurement errors, the two subpopulations are found to be coeval. Combined with previous spectroscopic age determinations for M87 GCs, our results favor a picture in which the GCs associated with this galaxy are formed at high redshift and within a period of a few gigayears.

Subject headings: galaxies: formation — galaxies: individual (M87) — galaxies: star clusters

1. INTRODUCTION

Globular clusters (GCs) are among the oldest stellar systems in the universe. Their large numbers around early-type galaxies, their ease of detection, and their simplicity as single-age, monometallic stellar populations make them ideal tracers of the evolutionary history of their host galaxies. A key result that has emerged from observations of GC systems is that a large fraction of early-type galaxies show a bimodal distribution in broadband color (e.g., Gebhardt & Kissler-Patig 1999). As broadband colors of old stellar populations are much more sensitive to metallicity than age, this bimodality indicates the presence of two GC subpopulations, a metal-rich and a metal-poor, but owing to the age-metallicity degeneracy (e.g., Worthey 1994) no firm conclusion can be drawn on the ages of the two components based on broadband colors alone. Several models have attempted to explain the bimodality in terms of a particular galaxy formation process: major mergers of late-type galaxies (Ashman & Zepf 1992), two bursts of in situ star formation (Forbes, Brodie, & Grillmair 1997), and hierarchical formation (Côté, Marzke, & West 1998). The first two models form the metal-rich GCs out of a second burst of star formation, while the third assumes that the GC system is assembled via dissipationless mergers.

A key observational constraint on those models is the relative ages of the GC subpopulations. Multiple metallicity populations do not necessarily require separate bursts of star formation but may also reflect differences in the environment where the GC subpopulations formed. Elucidating the formation histories of the GC subpopulations on the basis of age can help discriminate between the proposed models.

Most previous determinations of the ages of the GC subpopulations in undisturbed early-type galaxies seem to suggest coeval subpopulations (Kissler-Patig et al. 1998; Cohen, Blakeslee, & Ryzhov 1998; Puzia et al. 1999; Larsen et al. 2002), albeit usually with large uncertainties. For M87, there have been conflicting claims. Cohen et al. (1998) obtained Keck spectroscopy of 150 GCs in M87 and found no sign of a variation in age with metallicity, excluding the possibility that one population is half as old as the other at the 99% confidence level. On the other hand, Kundu et al. (1999) estimate using *V* and *I* photometry from the *Hubble Space Telescope* (*HST*) that the metal-rich clusters are 3–6 Gyr younger than their metal-poor counterparts.

We have obtained Strömgren photometry of the GC system in the inner part of M87. By combining a metallicity-sensitive color index with the turnover *u*-band luminosity of the GC luminosity function (GCLF) of the two subpopulations, we have measured their relative age by comparing our observations with population synthesis models. We find the two GC subpopulations to be coeval within our measurement errors, in agreement with the spectroscopic estimates.

2. OBSERVATIONS AND DATA REDUCTION

We used the Wide Field Planetary Camera 2 (WFPC2) on board *HST* to obtain Strömgren photometry (filters F336W, F410M, F467M, and F547M) of M87 (=NGC 4486), the giant elliptical galaxy near the dynamical center of the Virgo Cluster. The exposure times were 24 × 1200 s (F336W), 16 × 1200 s (F410M), 8 × 1200 s (F467M), and 8 × 1200 s (F547M). The field was positioned such that the nucleus of M87 falls in the PC. The raw data were processed with the standard Space Telescope Science Institute pipeline using the best available calibration.

In order to detect GCs against the background of light from M87, we constructed detection frames by subtracting a ring medianed image (Secker 1995) using radii of 5 pixels for the PC and 4 pixels for the WF. Detection was done with SExtractor (Bertin & Arnouts 1996), using Gaussian kernels as filters. All the detections were then photometered using DAOPHOT (Stetson 1987). We used an aperture of 2 pixels for the WF chips and 3 pixels for the PC. The sky was taken from an annulus between $r_i = 5$ pixels and $r_o = 8$ pixels.

The lists of detected objects were then matched with a matching radius of 0″.2 to produce a final catalog of GC candidates.

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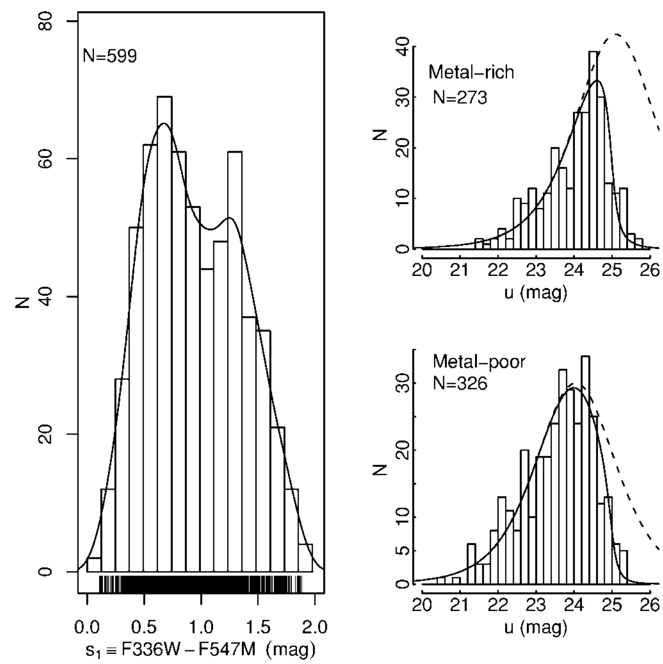

FIG. 1.—*Left*: GC s_1 color distribution for all GCs that lie in the range $0.1 < s_1 < 1.9$. The solid line is a density estimate using a normal kernel. *Right*: GCLF for the metal-rich and metal-poor subpopulations separated using s_1. The solid line is obtained by multiplying the best-fit t_5 distribution by the completeness function, which can be compared directly with the observations. The dashed line is the best-fit t_5; note the shift between the inferred LFs of both populations. Note that the turnover for the metal-rich population falls near 50% completeness, which falls at $u \sim 25$ mag.

To distinguish bona fide GCs from foreground stars and background galaxies, we used a method similar to the one employed by Kundu et al. (1999), which uses the flux ratio measured in apertures of 2 and 0.5 pixels: $r = f_2/f_{0.5}$. Detections were considered to be GCs if this ratio was in the range $1.5 < r < 12$ for the PC and $1.5 < r < 8.5$ for the WF chips. The matched list of GC candidates contained 628 objects.

Instrumental magnitudes were then corrected for charge transfer efficiency following the prescriptions of Whitmore, Heyer, & Casertano (1999). This correction was very small for F547M but could be as large as ~0.3 mag for the faintest GCs in F336W. Instrumental magnitudes were transformed to the VEGAMAG system using zero points taken from the *HST* Data Handbook. A correction for foreground extinction was performed using the reddening curves of Cardelli, Clayton, & Mathis (1989), with a value of $E(B-V) = 0.023$ taken from the DIRBE maps of Schlegel, Finkbeiner, & Davis (1998). In computing the aperture corrections for a 0.″5 radius, we selected ~60 isolated cluster candidates with photometric errors less than 0.05 mag and used DAOGROW (Stetson 1990) to compute the aperture corrections. A final correction of 0.1 mag was then applied to correct to infinite aperture (Holtzman et al. 1995).

We performed artificial star tests to determine the completeness function of our detections. The same objects that were used to derive the aperture corrections were used to create a point-spread function to model the GCs. We used DAOPHOT to add 50 GCs at a time to a given chip. The artificial images thus created were then subjected to the same reduction process as the real data. We added a total of 20,000 objects per chip and obtained the completeness function by fitting a function of the form $f(m|\alpha, m_l) = 0.5\{1 - \alpha(m - m_l)/[1 + \alpha^2(m - m_l)^2]^{1/2}\}$ (Fleming et al. 1995). In order to account for a dependence of the completeness function on the value of the galaxy halo light underlying the GCs, we divided the results from our artificial star tests according to the background level and measured the respective completeness functions. After some experimentation, we settled on separate completeness functions for objects with backgrounds above or below 1 ADU in the unfiltered image for both the PC and WF chips. The completeness function for the WF chips were very similar from chip to chip, so we treated them as one.

3. ANALYSIS

To measure the relative age of the GC subpopulations, we used a technique similar to that of Puzia et al. (1999). The idea is to estimate the turnover of the GCLF separately for the metal-rich and the metal-poor subpopulations; if the turnover reflects the same mass scale for both subpopulations, then we can compare the observed mean colors and turnover magnitudes with the predictions of population synthesis models to infer the mean metallicity and age for each subpopulation. Note that the mass at the turnover is *not* required since the models can be shifted arbitrarily in magnitude. Provided the assumption of equal masses at the turnover is valid, the relative age follows from the models regardless of the specific value of the GC turnover mass.

Puzia et al. (1999) used *V* and *I* photometry from *HST* to implement this technique. We exploit the enhanced fading of stellar populations with age in the *u* band, and a more sensitive metallicity index, to improve the sensitivity of the technique. We used two different indices in our analysis: $s_1 \equiv m_{\rm F336W} - m_{\rm F547M}$ and $s_2 \equiv m_{\rm F336W} + m_{\rm F410M} - m_{\rm F467M} - m_{\rm F547M}$. The latter has greater metallicity sensitivity, but the ratio of the sensitivity to the typical photometric error in each index is approximately the same for both.

To reduce the background contamination, we restricted the GC sample by imposing a cut in color: we included in the analysis only those GC candidates that lie in the range $0.1 < s_1 < 1.9$ or $0.3 < s_2 < 3.0$; this reduces the sample by ~5%. Owing to the small size of the field and the large number of GCs present on it, contamination in the final sample is expected to be very small. A histogram of the s_1 color distribution and a normal kernel density estimate (Silverman 1986) is shown in Figure 1. Bimodality is seen clearly in both distributions, and this is confirmed by a KMM test (Ashman, Bird, & Zepf 1994), which accepts the hypothesis of bimodality at 99.9% confidence.

To separate the color distribution into a metal-rich and a metal-poor sample, and to obtain the color of the peaks of each population, we used the output of KMM, which returns a mean color for each subpopulation and a value that divides the sample based on an a posteriori likelihood. We also obtained estimates of the peaks and the dividing point using a normal kernel density estimate, which returned values in good agreement with those from KMM. The values adopted to separate the subpopulations are 0.97 mag for s_1 and 1.5 mag for s_2. The mean colors for both subpopulations are listed under $m_{\rm col}$ in Table 1.

Having divided the sample into metal-rich and metal-poor subpopulations, we used a maximum likelihood method in order to estimate the turnover of the *u*-band GCLF for each subpopulation. Explicitly, if we denote the parametric representation of the intrinsic LF by $\Phi(u|\Theta)$, where Θ is the set of parameters that determine the LF, and the completeness function by

TABLE 1
OBSERVED AND DERIVED PROPERTIES OF M87 GLOBULAR CLUSTERS

	Metal-poor		Metal-rich			Relative Age[b] (Gyr)		
Index	m_{col}	m_{TO}	m_{col}	m_{TO}	IMF[a]	M98	W94	BC93
s_1	0.67 ± 0.015	24.04 ± 0.09	1.27 ± 0.017	25.09 ± 0.15	S55	1.3 ± 3.1	−1.9 ± 3.0	1.8 ± 3.2
	0.67 ± 0.015	24.04 ± 0.09	1.27 ± 0.017	25.09 ± 0.15	MS79	...	−1.3 ± 2.3	−0.5 ± 2.2
	0.67 ± 0.015	24.04 ± 0.09	1.27 ± 0.017	25.09 ± 0.15	GBF97	0.0 ± 3.2	...	...
s_2	1.07 ± 0.024	23.99 ± 0.09	1.95 ± 0.027	25.00 ± 0.14	S55	1.5 ± 2.7	−1.4 ± 2.7	2.5 ± 2.9
	1.07 ± 0.024	23.99 ± 0.09	1.95 ± 0.027	25.00 ± 0.14	MS79	...	−0.4 ± 2.2	−0.1 ± 2.1
	1.07 ± 0.024	23.99 ± 0.09	1.95 ± 0.027	25.00 ± 0.14	GBF97	0.4 ± 2.7	...	...

[a] S55 = Salpeter 1955; MS79 = Miller & Scalo 1979; GBF97 = Gould et al. 1997.
[b] M98 = Maraston 1998; W94 = Worthey 1994; BC93 = Bruzual & Charlot 1993.

$f(u|b)$, where b is the background level, we maximize the likelihood

$$L(\Theta) = \prod_{i=1}^{n} A_i \Phi(u_i|\Theta) f(u_i|b_i),$$

where A_i is a normalization factor. For $\Phi(u|\Theta)$, we used a Student t_5 distribution, $\Phi(u|\mu,\ \sigma_t) = (8/3\sqrt{5}\pi\sigma_t)[1 + (u-\mu)^2/5\sigma_t^2]^{-3}$, which has been shown to be a better fit to the Milky Way (MW) GCLF than a normal distribution (Secker 1992). We let σ_t be free, or fixed at $\sigma_t = 1.1$ mag (equivalent to $\sigma_g = 1.4$ mag for a Gaussian distribution), which is consistent with the value obtained for M87 by Kundu et al. (1999), $\sigma_g = 1.39 \pm 0.06$ mag. The fit with two free parameters confirmed that the choice of $\sigma_t = 1.1$ mag is supported by our data for both subpopulations, so in subsequent analysis we used the one-parameter fit. Uncertainties were calculated both with a bootstrap procedure and using the maximum likelihood surface around the minimum. The results for the turnovers are presented in Table 1 under m_{TO} for

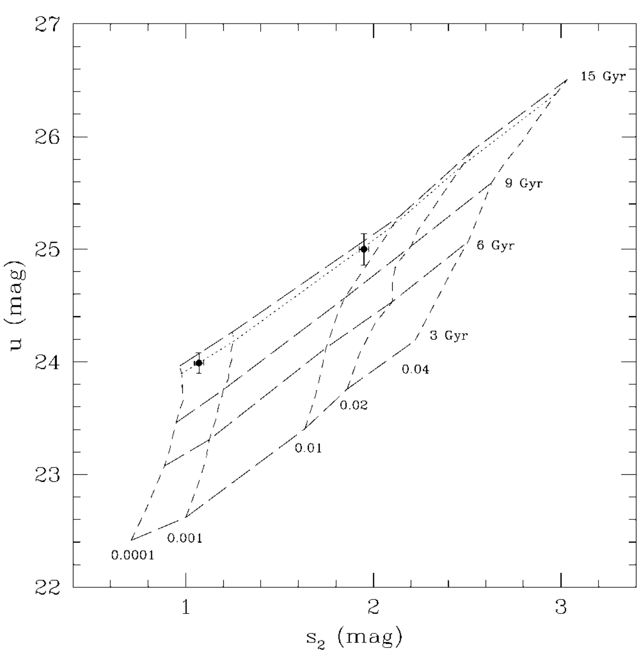

FIG. 2.—Determination of the relative ages of the GC populations using the Maraston (1998) models with a Gould et al. (1997) IMF. The short-dashed lines are isometallicity tracks of $Z = 0.0001$, 0.001, 0.01, 0.02, and 0.04, and the long-dashed lines are isochrones of 3, 6, 9, and 15 Gyr. The filled circles are at the estimated turnover luminosities and mean s_2 color for both populations; the error bars are 1 σ uncertainties. The dotted line is the isochrone of 14 Gyr where the blue population has been assumed to lie. The age for the red population, and thus the relative age, is then interpolated from the grid. (Some isochrones have been omitted for clarity.)

both GC subpopulations. Varying the turnover estimation by letting both μ and σ_t be free and using a Gaussian distribution ($\sigma_g = 1.4$) instead of a t_5 for $\Phi(u|\Theta)$ does not alter our conclusions. Likewise, disregarding the background dependence and considering a single completeness function $f(u)$ leads to similar results. Possible biases introduced by the difference between the intrinsic LFs and the assumed models will be investigated in future work (A. Jordán et al. 2002, in preparation).

4. RESULTS AND DISCUSSION

The turnover magnitudes for the metal-rich and metal-poor subpopulations of M87 and their respective mean colors were compared to the predictions of population synthesis models. We used the latest versions of the models of Bruzual & Charlot (1993), Maraston (1998), and Worthey (1994) to compute grids for every available metallicity. Because a particular value for the mass at the turnover is not assumed, the *absolute* ages for the subpopulations are unknown. Instead, the model grid was shifted in such a way that one of the subpopulations lies on the 14 Gyr isochrone, which is consistent with the age of the oldest MW GCs (VandenBerg 2000), and then the relative age was obtained by linearly interpolating from the model grid. Choosing another age for the oldest isochrone does not change our results significantly. A graphical example of the procedure can be seen in Figure 2. For each set of models, we tried two different initial mass functions (IMFs): a Salpeter (1955) and a Miller & Scalo (1979) for the Bruzual & Charlot (1993) and Worthey (1994) models and a Salpeter (1955) and a Gould, Bahcall, & Flynn (1997) for the Maraston (1998) models.

The results are summarized in Table 1, where the reported errors come from measurement uncertainties. We take the dispersion of the age differences for each color index, $\sigma \sim 1.5$ Gyr, as an indication of the systematic errors arising from the models. As the typical measurement error is 2–3 Gyr, and we have measurements using two color indices, the mean of our results gives a formal age difference of $\Delta t \equiv \mathrm{age_{blue}} - \mathrm{age_{red}} = 0.2 \pm 1.5$ (systematic) ± 2 (random) Gyr. Note that the quoted systematic uncertainty does not include possible differences in turnover masses; a 10% difference in the mass at the turnover would change the inferred age difference by ~1.5 Gyr.

Within the errors, all models are consistent with the two populations being coeval. The average metallicities obtained from the models for the subpopulations are $[\mathrm{Fe/H}]_{blue} = -1.58$ and $[\mathrm{Fe/H}]_{red} = -0.30$, in reasonable agreement with the values $[\mathrm{Fe/H}]_{blue} = -1.41$ and $[\mathrm{Fe/H}]_{red} = -0.23$ obtained by Kundu et al. (1999). Cohen et al. (1998) found no variation of age with metallicity from their Keck spectra of M87 GCs, for which they find a mean age of 13.2 Gyr. Dividing the results presented in their Table 4 into two populations and averaging the results gives a formal age difference of $\Delta t \sim 1$ Gyr with a typical uncertainty in their age estimates of ∼2 Gyr. Our results are in good agreement with theirs, and both are consistent with the subpopulations being coeval within the uncertainties. This is gratifying, as their sample of GCs is completely independent of ours and they are using a different set of diagnostics from the models. Indeed, as they determine absolute ages for each GC without making additional assumptions about the GC masses, the agreement may be taken as indirect evidence in support of our basic assumption that the GCLF turnovers for the different subpopulations correspond to approximately the same mass.

Although our observations were carried out in the same field as Kundu et al. (1999), we do not find support for their claim that the metal-rich subpopulation is 3–6 Gyr younger than the metal-poor. As no uncertainty is given for their estimate, we are not able to assess the significance of the disagreement, but none of the combinations of color indices, models, and IMFs that we have explored give a result that falls within their estimated range.

Our conclusions depend rather strongly on the assumption of equal mass at the turnover for both subpopulations. Even though the agreement with Cohen et al. (1998) and evidence from our Galaxy (McLaughlin & Pudritz 1996) suggest that this is a reasonable assumption, a direct test of this hypothesis for some early-type galaxies is not only desirable but within reach of efficient high-resolution spectrographs on 8 m class telescopes. It is also worth bearing in mind that the turnover for the metal-rich population in the u band falls near the level of ∼50% completeness. This makes the use of parametric modeling (including the completeness function) a necessity. Deeper observations will be required to observe the metal-rich turnover directly.

As evidence accumulates for the GC subpopulations of undisturbed giant elliptical galaxies being coeval (Kissler-Patig et al. 1998; Cohen et al. 1998; Puzia et al. 1999; Larsen et al. 2002), models that rely on well-separated epochs of star formation, either via major mergers or in situ bursts of star formation, appear less favored as a *generic* formation mechanism, unless one is willing to push the separation of the two epochs to the point of being almost coeval. This is not to say that major mergers of late-type galaxies are not a viable mechanism—populations of young GCs have almost certainly been identified in ongoing mergers (e.g., Whitmore & Schweizer 1995)—but their role as the primary mechanism for the formation of giant elliptical galaxies seems unlikely. Likewise, if two in situ star-forming bursts are to be the formation mechanism for bright elliptical galaxies, there has to be enough time for the metals to diffuse and enrich the gas from which the secondary GCs form. Lacking a specific mechanism that is responsible for regulating this star formation, it is hard to constrain this idea. Given the precision in the relative ages, the most we can say is that enrichment, outflows/inflows, and the star formation process must have occurred within approximately a few gigayears if this scenario is correct. Until a mechanism for producing precisely two bursts is identified, this scenario amounts to the *assumption* that two metallicity populations imply two periods of star formation.

Our results combined with those of Cohen et al. (1998) seem to show that whatever the assembly history of these galaxies, the GCs associated with M87 formed at an early time and within a short period. The presence of two populations differing in metallicity by a factor of ∼20, and yet with roughly the same age, suggests that the origin of the two populations may be related to differences in the local *environments* where the GC formed. According to the standard paradigm of structure formation, galaxies form via accretion and merging of small objects. Simulations predict a merger rate for massive cluster galaxies such as M87 that is highly peaked at redshifts $z \gtrsim 4$ (Gottlöber, Klypin, & Kravtsov 2001). This scenario provides the necessary difference in the local environments as the GCs can form in protogalactic fragments of varying mass. Simulations of the GC metallicity distributions based on this picture have been successful in reproducing the observations (Côté, West, & Marzke 2002). As the bulk of star formation is expected to happen early, and within approximately a few gigayears, this picture for the formation of bright elliptical galaxies appears consistent with the existing observations of their GC systems.

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