WASHINGTON CCD PHOTOMETRY OF THE GLOBULAR CLUSTER SYSTEM OF THE GIANT ELLIPTICAL GALAXY M60 IN VIRGO

MYUNG GYOON LEE,1 HONG SOO PARK,1 EUNHYEUK KIM,1 HO SEONG HWANG,1,2 SANG CHUL KIM,3 AND DOUG GEISLER4

Received 2007 July 15; accepted 2008 February 4

ABSTRACT

We present a photometric study of the GCs in the giant elliptical galaxy M60 in the Virgo Cluster, based on deep, relatively wide field Washington CT1 CCD images. The CMD reveals a significant population of GCs in M60 and a large number of young luminous clusters in NGC 4647, a small companion spiral northwest of M60. The color distribution of the GCs in M60 is clearly bimodal, with a blue peak at $(C - T_b) = 1.37$ and a red peak at $(C - T_r) = 1.87$. We derive two new transformation relations between the $(C - T_b)$ color and [Fe/H] using the data for the GCs in our Galaxy and M49. Using these relations, we derive the metallicity distribution of the GCs in M60, which is also bimodal: a dominant metal-poor component with center at [Fe/H] = −1.2, and a weaker metal-rich component with center at [Fe/H] = −0.2. The radial number density profile of the GCs is more extended than that of the stellar halo, and the radial number density profile of the blue GCs is more extended than that of the red GCs. The number density maps of the GCs show that the spatial distribution of the blue GCs is roughly circular, while that of the red GCs is elongated similarly to that of the stellar halo. We estimate the total number of the GCs in M60 to be 3600 ± 500 and the specific frequency to be $S_V = 3.8 ± 0.4$. The mean color of the bright blue GCs gets redder as they get brighter in both the inner and outer region of M60. This blue tilt is seen also in the outer region of M49, the brightest Virgo galaxy. Implications of these results are discussed.

Subject headings: galaxies: clusters: general — galaxies: individual (M60) — galaxies: photometry — galaxies: star clusters

Online material: color figures, machine-readable table

1. INTRODUCTION

Old globular clusters (GCs) keep the fossil record for the early epoch of their host galaxies as well as GCs themselves. By studying the age and metallicity of these GCs, we can investigate the formation and early evolution of their host galaxies as well as GCs themselves. GCs are distributed in a much wider region than the halo stars in their host galaxy, and thousands of them are found in giant elliptical galaxies (gEs). This feature, combined with easily derived velocity, makes GCs powerful probes with which to study the structure and kinematics in the outer halo of nearby gEs as well as the inner regions (see Lee 2003; Brodie & Strader 2006 and references therein).

While the GCs in the inner region of nearby gEs have been extensively studied using the Hubble Space Telescope (HST; Kundu & Whitmore 2001; Larsen et al. 2001; Peng et al. 2006; Mieske et al. 2006; Strader et al. 2006; Harris et al. 2006; Jordán et al. 2007), the GCs in the outer halo of nearby gEs have been studied using the wide-field camera in the ground-based telescopes (Lee & Geisler 1993; McLaughlin et al. 1993; Geisler et al. 1996; Lee et al. 1998; Rhode & Zepf 2001, 2004; Dirsch et al. 2004; Harris et al. 2004; Tamura et al. 2006a, 2006b; Bassino et al. 2006). However, the number of GCs for which these GCs were studied using the wide-field camera is still small.

Virgo, the nearest galaxy cluster, is one of the best targets for the study of GCs in gEs because it includes several gEs that are almost the same distance from us. We have been carrying a long-term photometric study of GCs in Virgo gEs using the Washington filter system (Lee & Geisler 1993; Geisler 1996; Lee et al. 1998). The Washington system is known to be very sensitive to measuring the metallicity of the GCs and has a wide bandwidth so that it is ideal for studying the metallicity of the extragalactic GCs (Geisler & Forte 1990). The results for the GCs in M87, the central dE in Virgo, were given in Lee & Geisler (1993), and those for the GCs in M49, the brightest gEs in Virgo, were given in Geisler et al. (1996) and Lee et al. (1998). Here we present the results for the third Virgo gE, M60 in this series. M60 was selected because it is one of the brightest gEs in Virgo and is therefore expected to possess a rich GC system.

M60 (NGC 4649) is only slightly less luminous ($M_V = −22.44$ mag) than two brightest Virgo galaxies M87 ($M_V = −22.62$ mag) and M49 ($M_V = −22.83$ mag). M60 is of morphological type E2 and is ultraviolet-bright, emitting strong flux at $\lambda < 2500$ Å (Bertola et al. 1982). A recent Chandra image of M60 shows that the diffuse X-ray emission is detected out to about 3′ from the center of M60, with a circular shape (Humphrey et al. 2006). Basic information on M60 is listed in Table 1. We adopted a distance to M60 of 17.3 Mpc ([g/H] = 3.19 ± 0.07) based on the surface brightness fluctuation method in Mei et al. (2007), for which the 1σ corresponds to 84 pc. Foreground reddening toward M60 is very small, $E(B-V) = 0.026$ (Schlegel et al. 1998), corresponding to $E(C-T_b) = 1.966 E(B-V) = 0.051$, and $A(V) = 0.071$, and $A(C) = 0.088$.

M60 has a companion SBc galaxy, NGC 4647, located 2.5′ from the center of M60 in the northwest direction (corresponding to a projected distance of $\sim 12.6$ kpc for the adopted distance to M60). The radial velocity of NGC 4647 ($v = 1422$ km s$^{-1}$) is 305 km s$^{-1}$ larger than that of M60 ($v = 1117$ km s$^{-1}$). White et al. (2000) found no foreground absorption due to NGC 4647 in the area of M60 and were unable to tell whether M60 or NGC 4647 is closer. Couture et al. (1991) performed the first photometric study based on $BV$ CCD imaging of the GCs in a small field ($2.1′ \times 3.4′$) of...
M60. They found a large dispersion in color distribution and a radial gradient in the mean cluster colors. They also found that the mean color of the GCs in M60 \((B - V) = 0.75\) is 0.1 mag redder than that of M49 \((B - V) = 0.65\). Harris et al. (1991) determined the \(B\)-band luminosity function up to \(B \sim 26\) mag of the GCs in this field and found that the GCs follow a more extended spatial distribution than the stellar light. Later, photometric studies based on HST WFPC2 and ground-based images revealed that the M60 GC system has a clear bimodality in the color distribution (Neilsen 1999; Kundu & Whitmore 2001; Larsen et al. 2001; Forbes et al. 2004). Forbes et al. (2004) found from the analysis of wide-field images obtained using Gemini GMOS that the red globular clusters (RGCs) have a similar surface density distribution to that of the stellar light, which is steeper than that of the blue globular clusters (BGCs). In addition, they derived a value for the specific frequency of the M60 GCs of \(S_N \sim 4.1 \pm 1.0\), which is lower than the value \(S_N \sim 6.7\) given in Ashman & Zepf (1998) based on inferior data.

Recently, it has been found that M60 is one of the galaxies that show a “blue tilt” in the color-magnitude diagram (CMD) of its GCs, in which the brighter the BGCs are, the redder they are in the mean (Harris et al. 2006; Strader et al. 2006; Mieske et al. 2006). Sarazin et al. (2003) and Randall et al. (2004) detected some discrete sources in M60 in the X-ray band using Chandra, and Randall et al. (2004) found that roughly 47% of the X-ray discrete sources are identified with GCs. By cross-correlating Chandra point sources and optical GC candidates, Kim et al. (2006) found that the mean probability for a GC to harbor a low-mass X-ray binary (LMXB) in M60 is about 6.1% \(\pm 1.0\), and that this probability for the RGCs is much larger than that for the BGCs. In addition, Pierce et al. (2006) published a spectroscopic study of 38 GCs in M60 based on data obtained using Gemini GMOS, and Bridges et al. (2006) presented a study of the GC kinematics of M60 using these data.

In this paper we present a photometric study of GCs in M60 using deep, relatively wide field CCD photometry. This study covers a field of M60 that is much larger than any previous studies on GCs in M60 and uses the Washington system, which has a better sensitivity for measuring the metallicity compared with most other systems. This study supplements also our kinematic studies of the GCs in M60 (Lee et al. 2008; Hwang et al. 2008). This paper is organized as follows. In 2 we describe our observations and data reduction. In 3 we present the CMD and color distribution of the GCs and compare the surface photometry of the stellar halo with the structure of the GC system. We also investigate the radial variation of the mean magnitudes and colors of the GCs and estimate the total number and specific frequency of the GCs. In 4 we discuss our results and their implication in comparison with other studies. Primary results are summarized in the final section.

2. OBSERVATIONS AND DATA REDUCTION

2.1. Observations

CCD images of M60 were obtained on the photometric nights of 1997 April 9 and 10 (UT) at the Kitt Peak National Observatory (KPNO) 4 m telescope using the 2048 × 2048 pixel CCD camera at the prime focus. Washington \(C\) and Kron-Cousins \(R\) filters were used. The Kron-Cousins \(R\) filter has a very similar effective wavelength to that of the Washington \(T_1\) filter, but with a much wider bandwidth resulting in 3 times the sensitivity (Geisler 1996). Geisler (1996) showed that \(T_1\) reproduces \(R\) magnitude very well: \(R = T_1 + 0.003 - 0.017(C - T_1)\) with rms = 0.02. So we used the \(R\) filter as an alternative to the \(T_1\) filter, as done in most recent Washington studies (Geisler 1996; Lee et al. 1998; Dirsch et al. 2004; Harris et al. 2004; Bassino et al. 2006).

The observation log is given in Table 2. The size of the field of view is 16.4’ × 16.4’, and the pixel scale is 0.47” pixel\(^{-1}\). Exposure times are 100 s and 4 × 1500 s for \(C\) and 60 s and 3 × 1000 s for \(T_1\). Each long-exposure image was taken with dithering of 10’’–28’’. The seeing ranged from 1.1’’ to 1.5’’. In addition, several Washington standard fields in Geisler (1996) were observed during the observing run.

2.2. Point-Source Photometry

Each frame was trimmed, bias-subtracted, and flat-fielded with twilight sky flats for \(C\) and dome flats for \(T_1\) using the IRAF software. The individual long-exposure images in each filter were

### Table 1

| Parameter | Values | References |
|-----------|--------|------------|
| R.A., decl. (J2000.0) | 12h43m39.66s, +11°33’ 9.4’’ | 1 |
| Effective radius, \(R_{\text{eff}}\) | 97’’ (C), 110’’ (\(T_1\)) | 2 |
| Effective ellipticity, \(e_{\text{eff}}\) | 0.21 (C, \(T_1\)) | 2 |
| P.A. (\(R_{\text{eff}}\)) | 106° (C), 105° (\(T_1\)) | 2 |
| Standard radius, \(R_{25}\) | 242’’ (C) | 2 |
| Standard ellipticity, \(e_{25}\) | 0.224 (C) | 2 |
| P.A. (\(R_{25}\)) | 108° (C) | 2 |
| Total magnitudes | \(V^* = 8.84 \pm 0.05, B^* = 9.81 \pm 0.05\) | 3 |
| X-ray luminosity | \(\log(L_X/\text{ergs s}^{-1}) = 41.16\) | 4 |
| Systemic radial velocity, \(v_p\) | 1117 ± 6 km s\(^{-1}\) | 1 |
| Foreground reddening | \(E(B - V) = 0.026\) | 5 |
| Distance | \(d = 17.30\) Mpc \(\left[m - M \right] = 31.19 \pm 0.07\) | 6 |

### Table 2

| Target | Filter | \(T(\text{exp})\) | Air Mass | Seeing (arcsec) | Date (UT) |
|--------|--------|-----------------|----------|---------------|-----------|
| M60... | C      | 100             | 1.4      | 1.43          | 1997 Apr 9|
| M60... | C      | 1500            | 1.5      | 1.47          | 1997 Apr 9|
| M60... | R      | 60              | 1.3      | 1.43          | 1997 Apr 9|
| M60... | R      | 1000            | 1.4      | 1.35          | 1997 Apr 9|
| M60... | C      | 3 × 1500        | 1.2      | 1.09–1.24    | 1997 Apr 10|
| M60... | R      | 2 × 1000        | 1.4      | 1.34–1.44    | 1997 Apr 10|
then shifted to a common center and medianed together. Figure 1 displays a gray-scale map of the short-exposure $T_1$ image of M60.

GCs at the distance of M60 appear as point sources in our images. First, we subtracted the stellar halo of M60 from each of the original images for better detection of the sources as follows. We created a model image of M60 using the $\texttt{ellipse}$ task in IRAF STSDAS. Then we subtracted the model image from the original image to remove the stellar halo light. We detected objects in the WFPC2 images and derived the photometry of the detected objects using the digital photometry software HSTPHOT (Dolphin 2000). We used 3.5 $\sigma$ as a threshold for detection in the $HST$ images. We used the radii of the aperture of 3 pixels for PC chips and 2 pixels for WF chips to get the aperture magnitudes of the detected objects and applied the aperture correction given by Kundu & Whitmore (2001) to get the total magnitudes of the detected objects. We selected the starlike sources in the list of the objects returned by HSTPHOT using $r_2$. We used the $HST$ photometry for the analysis of the central region ($r < 1.5''$) on one side of M60 for which the KPNO photometry is poor. We applied the same procedure to the images of another $HST$ WFPC2 field, at $5'$ north from the center of M60 (called the north $HST$ WFPC2 field), as marked in Figure 1 (for the basic information of this field see Kim et al. 2006). It is found that the number of GCs in this field is so small that they are of limited use for this study.

2.3. Standard Calibration

We derived the transformation equations for standard calibration from the photometry of the Washington standard stars observed during the same night. We obtained the instrumental magnitudes of the standard stars using the aperture radius of 7.5" as used in Geisler (1996). The standard transformation equations we derived are (April 9) $T_1 = t_1 + 0.034(c - t_1) - 0.122X + 0.282$ with $rms = 0.021$ and $N = 42$, and $(C - T_1) = 1.062(c - t_1) - 0.263X - 0.405$ with $rms = 0.018$ and $N = 44$, and (April 10) $T_1 = t_1 + 0.034(c - t_1) - 0.122X + 0.269$ with $rms = 0.028$ and $N = 39$, and $(C - T_1) = 1.062(c - t_1) - 0.263X - 0.425$ with $rms = 0.030$ and $N = 39$, where the uppercase letters represent the standard magnitudes, the lowercase letters the instrumental magnitudes (with a DAOPHOT system zero point of 25.0), and $X$ the air mass. We transformed the instrumental magnitudes of the sources onto the standard system using these transformation equations. We selected and listed in Table 3 the $CT_1$ photometry of 4497 point sources with $\sigma(C - T_1) < 0.3$ measured in the KPNO images, and Figure 2 displays the mean errors of $T_1$ and $(C - T_1)$ versus $T_1$ magnitude.

2.4. Completeness of the Photometry

We estimated the completeness of the KPNO photometry using DAOPHOT/ADDSTAR that was designed for the artificial star experiment. We generated a set of artificial stars for which the CMDs and luminosity functions are similar to the observational one, using the PSFs derived from the long-exposure real images. We did not include the central region at $r < 1'$ that was saturated in the real images. Then we added them to the real image avoiding the position of detected real objects. We added 1200 artificial stars to each pair of $C$ and $T_1$ images in a set of 50 pairs so that the total number of added artificial stars is 60,000. Then we applied the same procedure of photometry to the artificial images as used

![Gray-scale map of the Washington $T_1$ image of M60. The size of the field of view is 16.4' x 16.4'. North is up and east to the left. The small spiral galaxy in the northwest ($\Delta$R.A. = -109.9" and $\Delta$decl. = 107.3") of M60 is NGC 4647. The $HST$ WFPC2 fields are also marked by boxes.](image-url)
for the real images, and we estimated as the completeness factor the number ratio of the recovered artificial stars and the added artificial stars.

Figure 3 displays the completeness for $C$ and $T_1$ that we derived for the point sources. We plotted the completeness for the entire region and five bins in radial distance: $1' < r < 2'$, $2' < r < 3'$, $3' < r < 4'$, $4' < r < 5'$, and $5' < r < 6'$. It is seen that the completeness is higher than 90% for $T_1 = 23$ ($C = 24.3$) for the outer region at $r > 2'$ and $T_1 = 22.8$ ($C = 24.0$) for the inner region at $1' < r < 2'$. The photometric limit levels for 50% completeness are $T_1 = 24.4$ ($C = 25.4$) for the outer region at $r > 2'$ and $T_1 = 23.9$ ($C = 25.0$) for the inner region at $1' < r < 2'$. The completeness varies little depending on radius for the outer region at $r > 2'$, while it is somewhat lower for the inner region at $r < 2'$ compared with the outer region. We derived the mean photometric errors from the difference between the magnitudes of the added objects and recovered objects, finding that they are similar to the measured photometric errors for the real objects as seen in Figure 2. We derived similarly the completeness for V and $I$ using HSTPHOT, which is plotted also in Figure 3. The completeness for the HST photometry is higher than to 95% for $V < 23.5$ mag for the entire radial range of the HST data.

### Table 3

| ID  | $X^*$ (pixels) | $Y^*$ (pixels) | R.A. (deg) | Decl. (deg) | $T_1$ | $\sigma(T_1)$ | $(C - T_1)$ | $\sigma(C - T_1)$ |
|-----|----------------|----------------|------------|-------------|-------|----------------|-------------|-----------------|
| 2   | 182.38         | 457.14         | 190.806029 | 11.479574   | 17.714| 0.039          | 3.265       | 0.039           |
| 4   | 991.59         | 1164.33        | 190.908737 | 11.571802   | 17.898| 0.033          | 2.386       | 0.038           |
| 5   | 665.44         | 1204.13        | 190.865173 | 11.577062   | 17.925| 0.025          | 1.095       | 0.031           |
| 6   | 144.16         | 112.40         | 190.795517 | 11.434722   | 18.048| 0.063          | 3.753       | 0.066           |
| 7   | 862.64         | 923.39         | 190.891048 | 11.540276   | 18.060| 0.014          | 2.204       | 0.028           |

Notes.—Table 3 is published in its entirety in the electronic edition of the *Astrophysical Journal*. A portion is shown here for guidance regarding its form and content.

* $X$ and $Y$ increase toward east and north, respectively. A pixel corresponds to 0.47".

#### 2.5. Comparison with Previous Photometry

There is no previous Washington photometry of the sources in M60. However, there are a few photometries of the sources in M60 using the different filter systems in the literature. We derive the transformation relations between our Washington photometry and the $gi$ photometry given by Forbes et al. (2004).

Forbes et al. (2004) presented $gi$ photometry of the GCs in a field of about 90 arcmin$^2$ including M60, based on the CCD images taken using the Gemini North telescope. Our field of view covering 256 arcmin$^2$ is about 2.8 times larger than that of Forbes et al. (2004). We compared $(C - T_1)$ colors and $(g - i)$ colors for 396 objects with $T_1 < 22$ mag in common between this study and Forbes et al. (2004) as displayed in Figure 4. Figure 4 shows that the relation between $(g - i)$ colors and $(C - T_1)$ colors can be fitted by a triple linear relation as follows: $(g - i) = 0.735(C - T_1) - 0.121$ with rms = 0.110 for $0.2 < (C - T_1) < 1.2$, $(g - i) = 0.527(C - T_1) + 0.119$ with rms = 0.092 for $1.2 < (C - T_1) < 2.4$, and $(g - i) = 1.372(C - T_1) - 1.943$ with rms = 0.243 for $2.4 < (C - T_1) < 4$. In addition, the transformations between magnitudes are derived to be $g = C + 0.340 - 0.548(C - T_1)$ with rms = 0.067 and $I = T_1 + 0.429 - 0.199(C - T_1)$ with rms = 0.070.

We also derived the transformation between $(C - T_1)$ colors and $(V - I)$ colors for the objects with $T_1 < 22$ mag in common between the KPNO images and HST WFPC2 images, as shown in Figure 4. They show a linear relation for the color range of $0.9 < (C - T_1) < 2.4$. Linear fitting to the data for 72 objects with small errors $[\sigma(C - T_1) < 0.1]$ yields $(V - I) = 0.407(C - T_1) + 0.459$ with rms = 0.047 for $0.9 < (C - T_1) < 2.4$. This is in very good agreement with the result derived from the photometry of M49 (NGC 4472) by Lee & Kim (2000), $(V - I) = 0.443(C - T_1) + 0.396$ for $(C - T_1) < 2.6$. We also derived an approximate relation for the magnitudes, $V = T_1 - 0.106 + 0.243(C - T_1)$ with rms = 0.100 for 66 objects with $0.9 < (C - T_1) < 2.4$.

#### 3. RESULTS

##### 3.1. Color-Magnitude Diagram

Figure 5 displays the CMDs of the measured point sources in the KPNO images of M60 (in three regions at $1.5' < r < 7'$, $7' < r < 9'$, and $9' < r < 10'$, where $r$ is the projected galactocentric distance), as well as those in the HST WFPC2 images (for $r < 1.5'$). We excluded the objects within a circular region of radial distance of $1'$ from the center of NGC 4647 from the KPNO data in Figure 5. We transformed the $(V - I)$ colors of the objects in the HST WFPC2 images into $(C - T_1)$ colors using the transformation equation in the previous section.

Three general kinds of objects are seen in Figure 5: (a) GCs of M60 residing in the broad vertical feature in the color range of
1.0 < (C - T1) < 2.4, (b) a small number of bright foreground stars at (C - T1) ≤ 0.9 and (C - T1) ≥ 2.6, and (c) faint blue unresolved background galaxies with T1 > 23 mag. Two vertical features are visible in Figure 5b at 1.5' < r < 7': BGCs and RGCs. We selected a sample of bright GCs with 1.0 < (C - T1) < 2.4 and 19 < T1 < 23 (−12.26 < M_{T1} < −8.26) for the analysis, considering the following points: (1) the color range of the known GCs in other galaxies is (C - T1)_0 ≈ 1−2.4, and the foreground reddening for M60 is small; (2) the peak luminosity of the GCs is estimated to be somewhat fainter than T ≈ 23 at the distance of M60 (see also § 3.7); (3) the mean photometric error is smaller than σ(T1) = 0.05 and the incompleteness in our photometry is estimated to be minor for T1 < 23; and (4) the contamination due to background galaxies is estimated to be very small for T1 < 23. The sample of GCs is separated around (C - T1) = 1.7, since the color boundary between the two components is estimated to be at (C - T1) = 1.7 as described in the following section. So we divided the entire sample of GCs into two classes: the BGCs with 1.0 < (C - T1) < 1.7 and the RGCs with 1.7 < (C - T1) < 2.4. A small number of the BGCs are still seen even at 9' < r < 10', while very few RGCs are visible in the same region.

Figure 6 displays the CMDs of the point sources within a radius of 1' from the center of the companion spiral galaxy NGC 4647 (top panel) and in a “control field” with the same area (bottom panel). The region for NGC 4647 is about 2.5' from the center of M60 so that it is unaffected by the saturation of the M60 nucleus in the image. The control field is located at the same radial distance from the center of M60, but in the opposite direction. We also checked the CMDs for two other control fields at the same radial distance but at different position angle (45° and 315°, respectively). They are very similar to the CMD for the chosen control field in Figure 6, so that the chosen control field can be considered to represent a control field for the statistical analysis. The number of objects within the boundary of bright GCs in the field of NGC 4647 (marked by the two rectangles) is slightly smaller than that in the control field, showing that most of the objects within the rectangles are probably GCs belonging to M60. Most of the point sources in NGC 4647 are much bluer than GCs, but as bright as GCs of M60.

Many more sources are seen that are slightly extended, compared with the point sources, in NGC 4647. We selected the extended sources using the criterion 1.27 ≤ r_{2} < 2 (note that
The color distribution is clearly bimodal. KMM tests of the data show that the probability that the color distribution is bimodal over unimodal is higher than 99.9%. We determined the following parameters for the best-fit double Gaussian curves describing the color distribution, using a maximum likelihood method through the KMM mixture modeling routine (Ashman et al. 1994): a primary component with center at \((C - T_1) = 1.37\) and width \(\sigma = 0.16\) and a secondary component with center at \((C - T_1) = 1.87\) and \(\sigma = 0.23\). We did not assume equal dispersions for the blue and red globular subpopulations in these KMM fits, and they do indeed appear to be significantly different.

The minimum between the two components is found to be at \((C - T_1) = 1.7\), which was used for dividing the entire sample into BGCs and RGCs. This boundary color is slightly redder than that used for M49 (Geisler et al. 1996; Lee et al. 1998) but is consistent with the finding by Couture et al. (1991) based on \(BV\) photometry of GCs in M60. They also found that the mean color of the GCs in M60 \([\langle B - V \rangle = 0.75\] is 0.1 redder than that of M49 \([\langle B - V \rangle = 0.65\].

We investigate the radial variation of the color distribution of the bright GCs after subtracting the background level derived from the region at \(9'< r < 10'\) in Figure 8. In the central region at \(r < 75''\), the RGC component looks stronger than the BGC component, while the BGC component begins to dominate for \(r > 2'\) and steadily strengthens its domination in the outer region. The RGC component is barely seen in the background region at \(9'< r < 10'\).

We also derived the variation of the ratio of the number of the bright BGCs to the number of bright RGCs with \(r < 7'\), plotting it in Figure 9. Figure 9 shows that this ratio keeps increasing as the galactocentric radii increase and is fitted well by the linear relation \(N(\text{BGC})/N(\text{RGC}) = 0.43(\pm 0.04)r + 0.47\). This ratio becomes unity at \(r = 74''\).

3.3. Galaxy Surface Photometry

We derived the surface photometry of M60 from the KPNO images using the elliptical task in IRAF STSDAS. First, we masked out bright foreground stars and nearby galaxies including NGC 4647 in the original images. Then we applied elliptical for ellipse fitting of the isophotes of M60 to the resulting images. We used the very outer region at \(r \sim 10'\) in the corner of the image to estimate the background level. We measured the median intensity value for each of three regions in the corner and took the median of the three median values as the background level. The central part \((r < 3'\) of the short-exposure \(T_1\) image of M60 was saturated so that we could not derive the color for this region. The radial profiles of the surface color were obtained using the same structural parameters for both \(C\) and \(T_1\), which were derived from the \(T_1\) images. The errors for the surface brightness magnitudes are those that are given by elliptical, not including the errors for the background estimate.

Figure 10 displays the radial profiles of the surface brightness magnitudes, \((C - T_1)\) color, ellipticity, and position angle (P.A.) of M60 as a function of major radius \(r_{\text{maj}}\). We fit the surface brightness profiles with a de Vaucouleurs \(r^{1/4}\) law for the range of \(3.8'' < r_{\text{maj}} < 410.1''\), using linear least-squares fitting: \(\mu(C) = 2.568(\pm 0.011)r^{1/4} + 14.955(\pm 0.032)\) with rms = 0.065, and \(\mu(T_1) = 2.649(\pm 0.012)r^{1/4} + 12.832(\pm 0.034)\) with rms = 0.069, which are also plotted by the solid lines in the same figure. It is found that the surface brightness profiles are well fitted by a de Vaucouleurs \(r^{1/4}\) law. The effective radius and standard radius for C band [where \(\mu(C) = 25.0\) mag arcsec\(^{-2}\)] are derived to be 97'' and 242'', respectively, corresponding to linear sizes of 8.15 and 20.3 kpc.
The \( (C/T_1) \) color gets bluer in the inner region \( r < 150 \) as the galactocentric radius increases, and it remains almost constant in the outer region. This trend for the inner region is consistent with the radial variation of \( (U/R) \) and \( (B/R) \) colors given by Peletier et al. (1990) as seen in Figure 10. The color trend at \( 3 < r < 151 \) can be fitted by the log-linear relation \( (C/T_1) = 0.162(\pm 0.032) \log r + 2.160(\pm 0.032) \) with rms = 0.065. The ellipticity increases rapidly from 0.1 to 0.2 in the central region and stays at an almost constant value in the outer region. The values of the ellipticity at the effective radius and standard radius are derived to be, respectively, 0.21 and 0.22. The P.A. increases from 90° to 100° in the central region and changes slowly in the outer region. The values of P.A. at the effective radius and standard radius are 106° and 110°, respectively.

### 3.4. Spatial Distribution of the Globular Clusters

We have investigated the spatial structure of the GC system in M60. Figure 11 displays the spatial distribution of the bright GCs with 19 mag \( < T_1 < 23 \) mag (all GCs, BGCs, and RGCs), as well as foreground stars found in the KPNO images. We also plotted the very blue bright clusters (YC) with \( (C/T_1) < 0.5 \) and 19 mag \( < T_1 < 23 \) mag. We selected the red point sources with \( (C/T_1) > 2.5 \) and \( T_1 < 23 \) mag as foreground stars for comparison. The spatial distribution of these objects is seen to be uniform in Figure 11b, showing indeed that they do not belong to M60. We also created number density maps of the GCs, which were smoothed and displayed in Figure 12. In Figure 12b we also display a grayscale map of the short-exposure \( T_1 \) image of M60 that shows the distribution of stellar light, which is to be compared with the GCs.

Several notable features are seen in Figures 11 and 12. First, the spatial distribution of all GCs is roughly circular, and it shows a strong central concentration. Second, the spatial distribution of the BGCs is roughly circular and extends farther than that of the RGCs. Third, the spatial distribution of the RGCs is somewhat elongated along the east-west direction, which is consistent with the position angle of the halo of M60. We derive \( e \) (ellipticity) = 0.05 ± 0.02, 0.03 ± 0.02, and 0.09 ± 0.04, respectively, for all GCs, BGCs, and RGCs at \( 1.5 < r < 7 \), using the dispersion ellipse method of Trumpler & Weaver (1953). Fourth, very blue, presumably young, bright clusters are located mostly within 1′ from the center of NGC 4647 (inside the small circle at the position of NGC 4647 in Fig. 11).

Fig. 5.— CMDs of the point sources in M60. The dashed line represents an approximate lower boundary of the KPNO photometry. The boxes represent the regions for selecting BGCs and RGCs with 19 mag \( < T_1 < 23 \) mag. (a) \( r < 1.5 \) in the HST WFPC2 images. (\( C/T_1 \)) is the color converted from \( (V-I) \). (b) \( 1.5 < r < 7 \) except for the circular region with radius of 1′ centered on NGC 4647. (c) \( 7 < r < 9 \). (d) Background \( (r > 9) \). [See the electronic edition of the Journal for a color version of this figure.]
3.5. Surface Number Density Profiles of the Globular Clusters

We have derived the radial profiles of the surface number density of bright GCs with 19 mag < \(T_1\) < 23 mag, using the KPNO data for the outer region at \(r > 1.5'\) and the \(HST\) data for the central region at \(r < 1.5'\). First, we checked the radial profiles of mean counts per unit area for the objects with the same range of magnitude and color as the GCs in the KPNO images, finding that they get almost flat at \(r > 8'\). Therefore, we derived the background levels from the mean surface number density of these objects at \(9' < r < 10'\): 1.988 ± 0.363 arcmin\(^{-2}\) for all GCs, 1.790 ± 0.344 arcmin\(^{-2}\) for the BGCs, and 0.199 ± 0.115 arcmin\(^{-2}\) for the RGCs. Then we subtracted these background values from the original number counts to produce the radial profiles of the net surface number density of GCs, which are listed in Table 4. We derived the surface number density profiles in the core region using the \(HST\) data with the same criteria as those for the KPNO data. We estimated the background contribution for the \(HST\) data using the result derived from the KPNO data, finding that it is negligible.

Figure 13 displays the radial profiles of the surface number density of GCs in comparison with the \(C\)-band surface brightness profile of M60. Several features are of note in Figure 13. First, the surface number density profile of all GCs extends farther than the surface brightness profile of the galaxy halo. Second, the surface number density profile of the RGCs agrees approximately with the surface brightness profile of the galaxy halo, although the halo is steeper. Third, the surface number density profile of the BGCs extends farther than that of the RGCs. Fourth, the surface number density profiles of the GCs in the outer parts at \(0.5' < r < 7'\) are fitted approximately both by the de Vaucouleurs \(r^{1/4}\) law \([\log \sigma = -1.974(\pm 0.047) r^{0.14} + 3.571(\pm 0.051)\] for all GCs, \(\log \sigma = -1.717(\pm 0.068) r^{0.14} + 2.984(\pm 0.074)\] for the BGCs, and \(\log \sigma = -2.262(\pm 0.050) r^{0.14} + 3.580(\pm 0.052)\] for the RGCs) and by a power law \([\log \sigma = -1.128(\pm 0.040) r + 1.563(\pm 0.011)\] for all GCs, \(\log \sigma = -1.128(\pm 0.040) r + 1.237(\pm 0.014)\] for the BGCs, and \(\log \sigma = -1.452(\pm 0.050) r + 1.281(\pm 0.016)\] for the RGCs). Effective radii are 8.09', 14.14', and 4.70' for all GCs, BGCs, and RGCs, respectively. Thus, the surface number density profile of the RGCs is much steeper than that of the BGCs.

Finally, the surface number density profiles of the GCs are flat in the central region at \(r < 0.5'\). This result is affected little by the incompleteness of our photometry because the completeness is higher than 95% for \(V < 23.5\) mag for the entire radial range of the \(HST\) data. This flattening indicates that the GC system is dynamically relaxed in the central region in the sense that the radial profile of the central region can be fitted by the King model (King 1962). Figure 14 shows the results derived from fitting the data for \(r < 2'\) with a King model. From error-weighted fitting we derive core radius \(r_c = 0.84'\) and concentration parameter \(c = 3.91\) for all GCs, \(r_c = 1.06'\) and \(c = 3.92\) for the BGCs, and \(r_c = 0.71'\) and \(c = 3.57\) for the RGCs. From equal-weighted fitting we derive similar results: \(r_c = 0.73'\) and \(c = 2.83\) for all GCs, \(r_c = 0.86'\) and \(c = 2.65\) for the BGCs, and \(r_c = 0.66'\) and \(c = 2.98\) for the RGCs. However, it is not easy to determine reliably the values of both parameters. If we adopt a fixed value, \(c = 2.5\), as done for the case of M87 by Kundu et al. (1999), we derive \(r_c = 0.85'\) for all GCs, \(r_c = 1.06'\) for the BGCs, and \(r_c = 0.72'\) for the RGCs. Thus, the core radius for the RGCs is much smaller than that for the BGCs. It is also noted that the surface number density profile of the RGCs at the outer area is reasonably fitted by the King model, while that of the BGCs at \(r > 3'\) shows a clear excess over the King model. The central flattening is also seen in the case of

---

**Figure 6.** \(T_1 - (C - T_1)\) CMDs of the point sources at \(r < 0.5'\) (filled circles) and \(0.5' < r < 1'\) (open circles) from the center of NGC 4647 (top) and the point sources in the “control field” with the same area at the same galactocentric distance from M60 as NGC 4647, but in the opposite direction (\(\Delta R.A. = 109.9'\) and \(\Delta Dec. = -107.3'\); bottom). In the top panel, filled squares and open squares represent slightly extended sources at \(r < 0.5'\) and \(0.5' < r < 1.0'\), respectively. Most of these sources are considered to be star clusters associated with NGC 4647. The boxes are the same as in Fig. 4. [See the electronic edition of the Journal for a color version of this figure.]

**Figure 7.** \(T_1 - (C - T_1)\) color distribution of the GCs with 19 mag < \(T_1\) < 23 mag at \(1' < r < 7'\) from M60. The thick solid line represents the double Gaussian fit to the data, each component of which is plotted by the dashed lines. The hatched histogram represents the color distribution of the background objects at \(9' < r < 10'\). [See the electronic edition of the Journal for a color version of this figure.]
Fig. 8.—Radial variation of the \((C - T_1)\) color distribution of the GCs with \(19 < T_1 < 23\) mag in M60 after background subtraction. Left: KPNO photometry. Right: HST WFPC2 photometry.
M49 (Lee & Kim 2000) and M87 (Kundu et al. 1999), both of which were also based on the HST WFPC2 data. The flattening for the GCs can be explained by the intrinsic property of the GC formation epoch (Harris et al. 1998) or by the effect of the GC destruction during the dynamical evolution (Côté et al. 1998). Kundu et al. (1999) concluded that there is little evidence supporting the latter in the case of M87, noting that the luminosity function of the GCs in M87 does not vary spatially within about 1.5′ from the center of M87. Therefore, the flattening for the M60 GCs may be the relic of the formation epoch of the GCs.

3.6. Radial Variation of Mean Magnitudes and Colors

Figure 15 displays the colors of the GCs with 19 < \( T_1 < 23 \) versus galactocentric distance derived from the KPNO data only. Mean and median colors of the GCs in each radial bin are represented by the larger symbols. The mean color of the entire sample of GCs shows a clear radial gradient, while those of the BGC and RGC show little, if any, radial gradients. Linear least-squares fitting for the range of 1′ < \( r < 9′ \) yields \( (C - T_1) = -0.033(\pm 0.003)r + 1.718 \) with rms = 0.020 for all GCs, \( (C - T_1) = -0.015(\pm 0.003)r + 1.457 \) with rms = 0.012 for the BGCs, and \( (C - T_1) = -0.008(\pm 0.002)r + 1.984 \) with rms = 0.009 for the RGCs. The samples at \( r < 1′ \) in the KPNO data suffer from incompleteness so that they were not included for fitting. The mean color of the stellar halo is much closer to that of the RGCs than to that of the BGCs for \( r < 8′ \), but it is 0.2–0.3 mag bluer than that of the RGC. This is in contrast to the case of M49, where the color profiles of the RGCs agree well with that of the stellar halo (Lee et al. 1998). The mean color for the RGCs depends on the color range adopted for taking a mean so that the color difference between the halo and the RGCs is not considered to be significant.

Figure 16 displays the \( C \) and \( T_1 \) magnitudes of the GCs with 19 mag < \( T_1 < 23 \) mag versus galactocentric distance from the KPNO data only. Mean magnitudes of the GCs in each radial bin are represented by the larger symbols. The mean magnitudes of the GCs with \( r > 1′ \) vary little as a function of galactocentric distance. The upper (bright side) envelope of the GC magnitude distribution also does not show any clear systematic radial gradient.

Linear least-squares fitting for the range of 1′ < \( r < 9′ \) yields \( T_1 = 0.007(\pm 0.008)r + 21.945 \) with rms = 0.053 for all GCs, \( T_1 = 0.012(\pm 0.017)r + 21.881 \) with rms = 0.058 for the BGCs, and \( T_1 = 0.033(\pm 0.013)r + 21.866 \) with rms = 0.050 for the RGCs. The samples at \( r < 1′ \) suffer from an incompleteness problem so that they were not included for fitting. Thus, we find little or no dependence of the mean magnitude of the GCs on galactocentric distance.

3.7. Luminosity Function and Specific Frequency

Figure 17 displays the luminosity function of the GCs in M60. We plot the luminosity function of the GCs at 1.5′ < \( r < 8′ \) derived from the KPNO photometry, the luminosity function of the background objects with the same color range as that of the GCs at 9′ < \( r < 10′ \), and the net luminosity function for 1.5′ < \( r < 8′ \) that was derived after subtracting the background luminosity function from the luminosity function of the GCs. The luminosity functions were corrected for incompleteness using the completeness values derived in § 2. We also plot the luminosity function of the GCs at \( r < 1.5′ \) derived from the HST photometry. The HST luminosity function of the GCs at \( r < 1.5′ \) was derived by counting the GCs in a half circle of radius \( r < 1.5′ \) and doubling the resulting counts. The KPNO luminosity function is similar to that of the HST luminosity function for the bright magnitude range \( T_1 < 23.5 \), showing a peak at \( T_1 \approx 23 \). For \( T_1 > 23.5 \), the KPNO luminosity function falls below the HST luminosity function, indicating that the KPNO photometry gets more incomplete in the faint magnitude range. Larsen et al. (2001) derived the peak magnitude of the luminosity function of the GCs in the central region of M60 from the HST WFPC2 data: \( V(\text{peak}) = 23.58 \pm 0.08 \), which corresponds to \( T_1 = 23.38 \) adopting the color \( (C - T_1) = 1.7 \) in the equation given in the previous section and the foreground reddening \( A_V = 0.088 \). This value is consistent with the peak magnitude seen in the KPNO luminosity function.

We derived an estimate of the total number of GCs by (1) counting the brighter half of the luminosity function, which is almost complete, and (2) doubling it after subtracting background contribution, assuming that the luminosity function of the GCs is symmetric around the peak magnitude. The number of GCs brighter than the peak magnitude (19 < \( T_1 < 23.383 \)) at \( r < 8′ \) is 2048: 366 at \( r < 1.5′ \) from the HST images and 1682 at \( 1.5′ < r < 8′ \) from the KPNO images. We then derived the number of point sources with the same color as the GCs in the background region at \( 9′ < r < 10′ ; 40 \). If this number is scaled according to the area ratio of the regions at \( r < 8′ \) and \( 9′ < r < 10′ \), it becomes 475. Part of these objects may be GCs, but we do not know what fraction of them. So we arbitrarily assume one-half of these as GCs and assign the same value as an error. Then the total number of the GCs is estimated to be 2(2048 − 237.5) = 3621. We take \( N = 3600 \pm 500 \) as the total number of GCs in M60. This estimate is very similar to the value derived by Forbes et al. (2004), 3700 ± 900. From this value and the absolute magnitude of M60 (\( M_v = -22.44 \)) we derive the specific frequency to be \( S_N = 3.8 \pm 0.4 \), which is similar to the value given by Forbes et al. (2004), \( S_N \approx 4.1 \pm 1.0 \), and substantially smaller than the value given by Ashman & Zepf (1998), \( S_N \approx 6.7 \), based on inferior data. Our value, although on the small side for a cluster gE, is not atypical.

4. DISCUSSION

4.1. Comparison with Previous Studies

There is only one previous photometric study of the GCs of M60 covering a relatively large field, that of Forbes et al. (2004).
who covered about 90 arcmin$^2$. Forbes et al. (2004) showed that
the color distribution of 995 bright GCs with $20 < i < 23.6$ and
$0.5 < (g - i) < 1.5$ in M60 is bimodal, with peaks at $(g - i) = 0.865 \pm 0.005$ and $1.167 \pm 0.004$. These peak colors correspond
to $(C - T_1) = 1.416$ and 1.989, respectively, using the transformation equation between $(g - i)$ and $(C - T_1)$ given in § 2.5.
These values are similar to those derived in this study, $(C - T_1) = 1.37$ and 1.87. Note that the color range between these two populations is almost twice as large in $(C - T_1)$ as $(g - i)$, illustrating the former’s superior metallicity sensitivity (Geisler et al. 1996).

Forbes et al. (2004) also presented the surface number density profiles of the GCs for the range of galactocentric distance $1.3' - 3.8'$, showing that the RGCs with $0.5 < (g - i) < 0.9$ have a similar surface density distribution to that of stellar light, which is steeper than that of the BGCs with $1.1 < (g - i) < 1.5$. They found that the surface number density profiles of the BGCs, RGCs, and all GCs are fitted well by power laws with slopes of $-1.04 \pm 0.09$, $-1.73 \pm 0.06$, and $-1.3 \pm 0.05$, respectively. Their slopes for the BGCs and all GCs are similar to our estimates, $-1.128 \pm 0.040$ and $-1.285 \pm 0.034$, respectively, but their slope of the RGCs is somewhat steeper than ours, $-1.452 \pm 0.050$.

Forbes et al. (2004) presented also the radial variation of the mean colors of the GCs for the range of galactocentric distance $0.4' - 6.3'$, showing that both the BGCs and RGCs show little radial color gradient, while the color of all GCs gets bluer with increasing radius. Our results on the radial gradient of colors shown in Figure 15 are consistent with these results.

4.2. Metallicity Distribution

Colors of old GCs with similar ages are determined primarily by the metallicity of the GCs. There are several studies for deriving transformation relations between colors and [Fe/H] for GCs, which were based on the integrated photometry of the Galactic GCs, the combined data of GCs in a few galaxies, or stellar population synthesis models (Geisler & Forte 1990; Harris & Harris 2002; Cohen et al. 2003; Peng et al. 2006; Yoon et al. 2006).

However, there are only a few studies on the transformation relation between $(C - T_1)_0$ and [Fe/H] for GCs in the literature. Geisler & Forte (1990) presented a linear relation derived from the data for the Galactic GCs, $[Fe/H] = 2.35(C - T_1)_0 - 4.39$; Harris & Harris (2002) derived a quadratic relation based on the data for the Galactic GCs, $[Fe/H] = -6.037[1 - 0.82(C - T_1)_0 + 0.162(C - T_1)_0^2]$; and Cohen et al. (2003) derived another
quadratic relation based on the combined data including the GCs in M49 and M87, as well as the Galactic GCs, 

\[ [\text{Fe/H}] = -0.75(C - T_1)_0^2 + 4.438(C - T_1)_0 - 5.64. \]

However, the sequence for M87 GCs is not consistent with those of M49 GCs and Galactic GCs in the [Fe/H] versus \((C - T_1)_0\) diagram (Cohen et al. 2003), while the sequences for the latter two are consistent. The [Fe/H] data for 38 GCs in M60 presented by Pierce et al. (2006) show too large a scatter to be used for this purpose.

We derived new relations using the combined data for the GCs in our Galaxy and M49. The [Fe/H] data are from Harris (1996) for Galactic GCs and from Cohen et al. (2003) for M49 GCs. The \((C - T_1)\) data are from Harris & Canterna (1977) for Galactic GCs and from Geisler et al. (1996) and Lee et al. (1998) for M49 GCs. We updated the \((C - T_1)\) data for the Galactic GCs by adding our unpublished data for two GCs, NGC 6624 and NGC 6316, \((C - T_1) = 2.75 \pm 0.02\) and \(2.096 \pm 0.02\), respectively. We applied the reddening correction using the values given in Harris (1996).

Figure 18 displays an [Fe/H] versus \((C - T_1)_0\) diagram for these data. The sequence for the M49 GCs (open squares) matches well that for the Galactic GCs and covers as well the high [Fe/H] range, where there are only a few data for Galactic GCs. The relation between [Fe/H] and \((C - T_1)_0\) appears approximately linear over most of the range, with some possible curvature at both ends, especially at the metal-poor end. We tried to fit the combined data of our Galaxy and M49, after removing outliers, using various equations, and found that a third-order polynomial and double linear relations give the best fits:

\[ [\text{Fe/H}] = 1.387(C - T_1)_0^3 - 6.698(C - T_1)_0^2 + 12.609(C - T_1)_0 - 9.379 \]

with reduced \(\chi^2 = 2.529\), and

\[ [\text{Fe/H}] = (2.359 \pm 0.051)(C - T_1)_0 - 1.46 - 0.92 \]

for \((C - T_1)_0 \leq 1.46\),

\[ [\text{Fe/H}] = (1.951 \pm 0.044)(C - T_1)_0 - 1.46 - 0.92 \]

for \((C - T_1)_0 > 1.46\) with reduced \(\chi^2 = 5.090\). These relations are similar in general to those given in the literature, showing some difference only around the low- and high-metallicity ends. But note that the Cohen et al. (2003) curve is significantly displaced from the other relations at virtually all metallicities.

We derived [Fe/H] for M60 GCs from \((C - T_1)_0\) colors using our relations and previous relations (Geisler & Forte 1990; Harris & Harris 2002; Cohen et al. 2003) and displayed them in Figure 19. We plotted also the [Fe/H] distribution from Harris (1996) for the Galactic GCs for comparison in the same figure. Figure 19 shows several notable features as follows. First, the [Fe/H] distributions are very broad, covering from [Fe/H] \(\approx -2.4\) to much higher than the solar value, reaching [Fe/H] \(\approx 0.8\) and much higher than in the Galaxy. Second, all the [Fe/H] distributions derived
from various transformation relations show a dominant peak at $\frac{1}{2}\text{Fe/H} \approx -1.2$ dex. Third, none of the $[\text{Fe/H}]$ distributions derived from various transformation relations look symmetric. Most of them show clearly a weaker component at $[\text{Fe/H}] \approx -0.2$ dex in addition to the dominant peak at $[\text{Fe/H}] \approx -1.2$ dex, although the Harris & Harris (2002) calibration shows a dominant metal-rich peak. Thus, they are all bimodal in metallicity. A typical photometric error of $\sigma(C - T_1) = 0.1$ leads to an error $\sigma[\text{Fe/H}] = 0.20 - 0.24$ when using the two transformation relations derived in this study.

KMM tests of the data based on the third-order polynomial transformation show that the probability that the $[\text{Fe/H}]$ distribution is bimodal over unimodal is higher than 99.9%. We determined the parameters for best-fit double Gaussian curves to the metallicity distribution data for 1236 GCs, using a maximum likelihood method through the KMM mixture modeling routine (Ashman et al. 1994): a metal-poor component with center at $[\text{Fe/H}] = -1.18$, $\sigma = 0.42$, and $N = 779$, and a metal-rich component with center at $[\text{Fe/H}] = -0.27$, $\sigma = 0.59$, and $N = 467$ for the third-order polynomial transformation. Similar results are obtained for the double linear transformation: a metal-poor component with center at $[\text{Fe/H}] = -1.22$, $\sigma = 0.39$, and $N = 747$, and a metal-rich component with center at $[\text{Fe/H}] = -0.18$, $\sigma = 0.44$, and $N = 489$. Fourth, the metallicities of both peaks in M60 are 0.3–0.4 dex larger, respectively, than those for Galactic GCs at $[\text{Fe/H}] = -1.5$ and $-0.6$.

We compared $[\text{Fe/H}]$ derived using the double linear relation in this study with the estimates given by Pierce et al. (2006) for 38 common GCs, as shown in Figure 20. Pierce et al. (2006) derived $[\text{Fe/H}]$ of 38 GCs using two methods from spectra: one using the simple stellar population (SSP) models and the other using the Brodie & Huchra (BH) method (Brodie & Huchra 1990). Figure 20 displays SSP and BH metallicities given by Pierce et al. (2006) versus $[\text{Fe/H}]$ derived in this study. It is seen that two show good correlation but with some scatter. In addition, the $[\text{Fe/H}]$ of Pierce et al. (2006) is on average 0.3–0.4 dex lower than our
1. to the same galaxy cluster, being located at the similar distance

2. converted using (26

3. r

4. Table 4

5. Number Density Profiles of Globular Clusters

6. with 19 < T < 23 in M60

7. \( r \)

8. \( \sigma(\text{All GC})^{a} \)

9. \( \sigma(\text{BGC})^{a} \)

10. \( \sigma(\text{RGC})^{a} \)

11. \( 0.083 \ldots \) 115.870 ± 37.203 45.474 ± 23.529 70.394 ± 28.818

12. \( 0.292 \ldots \) 85.695 ± 16.463 33.950 ± 8.956 51.742 ± 11.915

13. \( 0.542 \ldots \) 78.312 ± 12.663 34.455 ± 8.495 43.855 ± 9.391

14. \( 0.833 \ldots \) 47.184 ± 6.602 20.670 ± 4.451 26.312 ± 4.876

15. \( 1.167 \ldots \) 29.771 ± 4.756 14.189 ± 3.363 15.580 ± 3.363

16. \( 1.750 \ldots \) 20.160 ± 2.082 10.668 ± 1.556 9.490 ± 1.383

17. \( 2.250 \ldots \) 14.561 ± 1.626 6.988 ± 1.178 7.571 ± 1.121

18. \( 2.750 \ldots \) 10.288 ± 1.258 5.496 ± 0.964 4.789 ± 0.808

19. \( 3.250 \ldots \) 9.890 ± 1.112 5.945 ± 0.894 3.942 ± 0.662

20. \( 3.750 \ldots \) 5.714 ± 0.799 2.586 ± 0.596 3.126 ± 0.532

21. \( 4.250 \ldots \) 5.339 ± 0.730 3.434 ± 0.613 1.903 ± 0.396

22. \( 4.750 \ldots \) 5.059 ± 0.677 3.241 ± 0.569 1.817 ± 0.367

23. \( 5.250 \ldots \) 3.921 ± 0.588 2.780 ± 0.514 1.140 ± 0.284

24. \( 5.750 \ldots \) 3.983 ± 0.565 2.846 ± 0.495 1.135 ± 0.271

25. \( 6.250 \ldots \) 1.990 ± 0.438 1.367 ± 0.388 0.620 ± 0.204

26. \( 6.750 \ldots \) 2.940 ± 0.472 1.906 ± 0.406 1.032 ± 0.241

27. \( 7.250 \ldots \) 2.086 ± 0.412 1.620 ± 0.375 0.465 ± 0.170

28. \( 7.750 \ldots \) 1.174 ± 0.355 0.425 ± 0.293 0.747 ± 0.201

29. \( 8.250 \ldots \) 1.040 ± 0.411 0.632 ± 0.365 0.405 ± 0.190

30. \( 8.750 \ldots \) 1.139 ± 0.493 0.831 ± 0.449 0.306 ± 0.204

31. \( a \) Number per square arcminute after background subtraction.

32. \( [\text{Fe/H}] \). Linear fits to the data yield SSP \( [\text{Fe/H}]^{a} = 1.120[\text{Fe/H}]^{(\text{this study})} - 0.232 \) with rms = 0.408 and BH \( [\text{Fe/H}]^{a} = 0.805[\text{Fe/H}]^{(\text{this study})} - 0.558 \) with rms = 0.315. The cause for this difference is not known.

33. 4.3. Comparison with M49 (NGC 4472)

34. There are several gEs in Virgo, and they are an excellent pool for studying the properties of the GCs in gEs because they belong to the same galaxy cluster, being located at the similar distance from us. M49 (NGC 4472) is the brightest gE in Virgo, located about 4° from the Virgo center. It is a prototypical example of a galaxy showing the bimodal color distribution of the GCs in gEs. Detailed analysis of the Washington \( C_{11} \) photometry of the GC system in M49 based on similar data was given by Geisler et al. (1996) and Lee et al. (1998). Here we compared in detail the properties of
the GC systems in M60 and M49, using very similar data and tech-
niques. We have also limited ourselves to almost identical GC sam-
ple definitions: 

$$r = 1' - 7'$$ and \( T_1 = 19 - 23 \). The color boundary for 
M49 \([C - T_1] = 0.9 - 2.3\] is 0.1 bluer than that for M60.

Figure 21 displays the color distribution of the bright GCs in 
M60 and M49. It shows that the color distributions of the bright 
GCs in both galaxies are similarly bimodal. We determined the 
parameters for best-fit double Gaussian curves to the color dis-
tribution data for M49, using a maximum likelihood method 
through the KMM mixture modeling routine: a primary compo-

dent with center at \([C - T_1] = 1.30, \sigma = 0.13, \text{and } N = 792, \) 
and a secondary component with center at \([C - T_1] = 1.79, \sigma = 0.21, \) 
and \( N = 818 \). One difference between M60 and M49 is that the 
peak colors for M60 \([C - T_1] = 1.37 \) and 1.87] are slightly redder 
than those for M49 \([C - T_1] = 1.30 \) and 1.79], which is consist-
tent with the finding by Couture et al. (1991) based on \( BV \) pho-
tometry. The difference in the foreground reddening between M60 
\([E(B - V) = 0.026, E(C - T_1) = 0.051]\) and M49 \([E(B - V) = 
0.022, E(C - T_1) = 0.043]\) is negligible (Schlegel et al. 1998).

Therefore, the colors of the GCs in M60 are considered to be on 
average about 0.1 mag redder than those in M49. If the GCs are of similar old ages, this implies that the M60 GCs are on average about 0.2 dex more metal-rich than their M49 counterparts.

Recently Strader et al. (2007) found from the reanalysis of the 
spectroscopic data for 47 bright GCs in M49 (Cohen et al. 2003) 
that the metallicity distribution of these GCs is bimodal with two 
peaks at \([\frac{\text{m}}{\text{H}}] = -1.1\) and 0.0. The peak metallicity for the metal-
poor GCs in M49 is \(0.4\) dex higher than that for the metal-poor 
GCs in our Galaxy, and the peak metallicity for the metal-rich 
GCs in M49 is \(0.5\) dex higher than that for the metal-rich GCs 
in our Galaxy. These results are similar to those derived from the 
Washington photometry of the GCs in M49 and M60 in this study.

The spatial distributions of the GCs in both galaxies share com-
mon features: (1) the RGCs are more centrally concentrated than 
the BGCs; (2) the GC system is more extended than the stellar halo; 
(3) the elongation of the RGC system is consistent with that of the 
stellar halo, while that of the BGC system is approximately cir-
cular; and (4) the color gradients in the overall GC systems are 
similar, as are the relative lack of color gradients in the individual 
RGC and BGC populations.

Recent studies based on the analysis of \( HST \) Advanced Camera 
for Surveys (ACS) WFC data for the GCs in elliptical galaxies 
found that the brighter the bright BGCs are, the redder their colors 
get, which has been referred to as the blue tilt (Harris et al. 2006;
Strader et al. 2006; Mieske et al. 2006). Interestingly, previous 
udies have found significant blue tilts in M87 and M60, but no 
evidence in M49 (Strader et al. 2006; Mieske et al. 2006). All
these results were based on the HST observation of small fields mostly covering the central regions of the galaxies. Mieske et al. (2006) found also that the blue tilts are seen in both inner regions (at \( r < 65'' \)) and “outer” regions (at \( r > 65'' \)) of bright galaxies, and that the slope for the GCs in the inner region is 2–3 times steeper in \( d(g - z)/dM_z \) than that in the outer region.

Figure 22 displays the CMDs of M60 and M49 derived from the KPNO images for the outer regions at \( 1.5' < r < 7' \). We used the data for M49 from Geisler et al. (1996) and Lee et al. (1998). We determined the parameters for the best-fit double Gaussian curves describing the color distribution for given magnitude range, using a maximum likelihood method through the KMM mixture modeling routine, and plotted the center values of the Gaussian components in Figure 22.

In Figure 22 the blue tilt is clearly seen for the bright BGCs in M60, while it is not clearly seen for the bright RGCs. Only the bright BGCs with \( T_1 \leq 22 \) in M60 show this blue tilt, which is consistent with the finding for the brightest cluster galaxies by Harris et al. (2006) that the bright BGCs with \( M_f \leq -9.5 \) show the blue tilt, while the faint BGCs \( M_f > -9.5 \) do not. The blue tilt is also seen for the bright BGCs with \( T_1 < 22 \) mag in M49, but it is much weaker than that for M60. The color change for the BGCs with \( 20 < T_1 < 22 \) is about 0.2 mag for M60, while it is about 0.1 mag for M49. However, the brightest bin for M60 is not separated clearly into two groups so that the difference in color change between M60 and M49 may not be significant. This is in contrast with the case of the inner region of M49 where no blue tilt was found in the HST ACS images (Strader et al. 2006; Mieske et al. 2006). Interestingly the RGCs in M49 also show a similar tilt like the BGCs, which is different from the typical CMD. Therefore, it is needed to investigate this problem with better data.

Several mechanisms were discussed for the origin of the blue tilt (Harris et al. 2006; Strader et al. 2006; Mieske et al. 2006; Bekki et al. 2007): accretion of GCs from low-mass galaxies, the capture of field stars by individual GCs, self-enrichment in GCs, contamination effect due to superstar clusters, stripped nuclei, and ultracompact dwarf galaxies (UCDs), and stochastic effects. After examining these, Mieske et al. (2006) concluded that self-enrichment and field star capture are the most promising to explain the observational results for the blue tilt derived from the HST ACS data for a sample of 79 early-type galaxies.

We discuss these two mechanisms in relation with the observational results for M60 and M49. If the blue tilt is mainly due to field star capture, it is expected that there is a radial variation of the blue tilt in the sense that it is steeper in the inner region. This is because there is a negative radial color gradient for halo stars at \( r < 2.5' \) as seen in the surface color profiles and because more massive GCs can collect more field stars that are redder in the inner region. However, it is not possible to investigate this trend reliably with the current data for M60 and M49.

On the other hand, the degree of self-enrichment is affected mainly by the mass of the stellar systems. So the self-enrichment effect of the GCs is expected to depend on the mass of the GCs, but little on the galactocentric distance. This is consistent with the observational results for the outer regions of M60 and M49. However, the existence of self-enrichment is seen in few, if any, typical GCs in our Galaxy and is a controversial subject (Thoul et al. 2002 and references therein). It is also difficult to explain the absence of the blue tilt in the inner region of M49 with self-enrichment. Further studies of GCs covering the full spatial extent of the GC systems of gEs are needed to understand this problem.

4.4. Implications for the Formation of Globular Clusters

Key observational facts for GCs in M60 to be explained by any formation scenario can be summarized as follows: (1) The color
Fig. 19.—Metallicity [Fe/H] distribution of the GCs in M60 (19 mag < \(T_1\) < 23 mag and 1' < \(r\) < 7'; circles), in comparison with the Galactic GCs (histogram). [Fe/H] was derived from the \((C - T_1)_{0}\) color using the following transformation relations: third-order polynomial equation (circles in [a]), double linear equation (circles in [b]) in this study, and Harris & Harris (2002) (circles in [c]), Cohen et al. (2003) (triangles in [c]), and Geisler & Forte (1990) (circles in [d]). In (a) and (b) smooth solid lines and dashed lines represent the Gaussian fits to the data. [See the electronic edition of the Journal for a color version of this figure.]
and the enrichment process might have been mainly continuous rather than double-episodal. However, the existence of a broad peak in the metallicity distribution (Beasley et al. 2002). The broad metallicity distribution and the high-metallicity peak being much weaker than the low-metallicity peak indicate, if anything, that the enrichment process might have been mainly continuous rather than double-episodal. However, the existence of a minor high-metallicity component indicates that there is a separate component of GCs that were formed in another episode. The color gradient of these GCs is very similar to that of the halo stars. These GCs in giant elliptical galaxies can be formed via a gaseous merger of galaxies. If they are formed via a gaseous merger, they must have been formed during the early phase of merging (within about 2 Gyr from the birth of their host galaxies). Later merging can make the host galaxies grow mostly in mass, not in metallicity (De Lucia et al. 2006). It is expected that the spatial distribution of these metal-rich GCs and halo stars is more centrally concentrated compared with that of the metal-poor GCs. The spatial distribution of the metal-rich GCs can be similar to or slightly more extended than that of the halo stars, depending on the formation timescale and dissipation effect of stars and GCs (see also Tamura et al. 2006b).

3. Tidal capture/accretion of the existing GCs.—Massive galaxies can collect GCs in the nearby surroundings that may include lower mass galaxies or the field. GCs accreted after about 1 or 2 Gyr from the first star formation can have any range of metallicity. However, most of the accreted GCs are probably metal-poor rather than metal-rich, since low-mass galaxies have generally more metal-poor GCs (Miller 2006), and they are more likely to be seen in the outer regions of massive galaxies.

**Fig. 20.—** Comparison of spectroscopic $[\text{Fe/H}]$ given by Pierce et al. (2006) and photometric $[\text{Fe/H}]$ derived using the double linear relation in this study for 38 common GCs in M60. Filled circles and open squares represent, respectively, $[\text{Fe/H}]$ derived using the SSP models and BH method by Pierce et al. (2006). The solid line and dashed line represent linear fits to the data for SSP $[\text{Fe/H}]$ and BH $[\text{Fe/H}]$, respectively, and the dotted line represents one-to-one correspondence. [See the electronic edition of the Journal for a color version of this figure.]

**Fig. 21.—** Comparison of the color distribution of the GCs with $19 < T_1 < 23$ mag and $1 < r < 7$ in M60 (this study; top) and M49 (Geisler et al. 1996; bottom). Solid lines represent double Gaussian fits, while the dashed lines represent the individual Gaussian components. [See the electronic edition of the Journal for a color version of this figure.]
Observational results for the GCs in M60 show features of all three processes. The metal-poor GCs are involved with the first and third processes, while the metal-rich GCs are related with the second process. Therefore, all three mechanisms may have played a role in the formation of the M60 GCs.

5. SUMMARY AND CONCLUSIONS

We have presented Washington C\text{I} photometry of the GCs in M60, as well as that of the star clusters in NGC 4647, a companion spiral galaxy, covering a 16.4' × 16.4' field. We have analyzed various photometric properties of the GCs in M60. Primary results are summarized as follows:

1. The CMD reveals a significant population of GCs in M60 and a large number of young luminous clusters in NGC 4647.
2. The color distribution of the GCs in M60 is clearly bimodal, with a blue peak at (C – T\text{I}) = 1.37 and a red peak at (C – T\text{I}) = 1.87.
3. We derived two new transformation relations between the (C – T\text{I})_0 color and [Fe/H] using the data for the GCs in our Galaxy and M49: a third-order polynomial relation, [Fe/H] = 1.387(C – T\text{I})_0^3 – 6.698(C – T\text{I})_0^2 + 12.609(C – T\text{I})_0 – 9.379, and a double linear relation, [Fe/H] = 2.359(C – T\text{I})_0 – 1.46 – 0.92 for (C – T\text{I})_0 ≤ 1.46, and [Fe/H] = 1.951(C – T\text{I})_0 – 1.46 – 0.92 for (C – T\text{I})_0 > 1.46. Using these relations, we derived the metallicity distribution of the GCs in M60, which is bimodal: a dominant metal-poor component with center at [Fe/H] ≈ −1.2, and a weaker metal-rich component with center at [Fe/H] ≈ −0.2.
4. The radial number density profile of the GCs is more extended than that of the stellar halo. The radial profiles for the outer region at 1' < r < 7' are fitted approximately equally well by the de Vaucouleurs law and a power law. The radial number density profile of the BGC is more extended than that of the RGCs. The radial profiles for the central region show flattening, and the radial profiles for r < 2' are well fitted by the King model. The core radii derived for the fixed concentration value of c = 2.5 are r_c = 0.85' for all GCs, r_c = 1.06' for the BGCs, and r_c = 0.72' for the RGCs. Thus, the core radius for the RGCs is much smaller than that for the BGCs.
5. The surface number density maps of the GCs show that the spatial distribution of the BGCs is roughly circular, while that of the RGCs is elongated similarly to that of the stellar halo.
6. The mean color of the bright BGCs gets redder as they get brighter in both the inner and outer regions of M60. This blue tilt is seen also in the outer region of M49, the brightest Virgo galaxy.
7. We estimated the total number of the GCs in M60 to be 3600 ± 500 and the specific frequency to be S_N = 3.8 ± 0.4.

The authors are grateful to the anonymous referee for very detailed and useful comments that improved the original manuscript significantly. This work was supported in part by a grant (R01-2007-000-20336-0) from the Basic Research Program of the Korea Science and Engineering Foundation. D. G. gratefully acknowledges support from the Chilean Centro de Astrofı́sica FONDAP No. 15010003.

Facilities: Mayall, HST (WFPC2)
REFERENCES

Ashman, K. M., Bird, C. M., & Zepf, S. E. 1994, AJ, 108, 2348
Ashman, K. M., & Zepf, S. E. 1992, ApJ, 384, 50
———. 1998, Globular Cluster Systems (Cambridge: Cambridge Univ. Press)
Bassino, L. P., Faifer, F. R., Forte, J. C., Dirsch, B., Richtler, T., Geisler, D., & Schuberth, Y. 2006, A&A, 451, 789
Beasley, M. A., Baugh, C. M., Forbes, D. A., Sharple, R. M., & Frenk, C. S. 2002, MNRAS, 333, 383
Bekki, K., Yahagi, H., & Forbes, D. A. 2007, MNRAS, 377, 215
Bertola, F., Capaccioli, M., & Oke, J. B. 1982, ApJ, 254, 494
Bridges, T., et al. 2006, MNRAS, 373, 157
Brodie, J. P., & Huchra, J. P. 1990, ApJ, 362, 503
Brodie, J. P., & Strader, J. 2006, ARA&A, 44, 193
Cohen, J. G., Blakeslee, J. P., & Coˆte´ , P. 2003, ApJ, 592, 866
Couture, J., Harris, W. E., & Allwright, J. W. B. 1991, ApJ, 372, 97
de Bruyne, V., Dejonghe, H., Pizzella, A., Bernardi, M., & Zeilinger, W. W. 2001, ApJ, 546, 903
De Lucia, G., Springel, V., White, S. D. M., Groton, D., & Kauffmann, G. 2006, MNRAS, 366, 499
de Vaucouleurs, G., de Vaucouleurs, A., Corwin, H. G., Jr., Buta, R. J., Paturel, H. G., & Fouque´ , P. 1991, Third Reference Catalog of Bright Galaxies ( New York: Springer)
Dirsch, B., et al. 2004, AJ, 127, 2114
Dolphin, A. E. 2000, PASP, 112, 1383
Forbes, D. A., Baugh, C. M., & Frenk, C. S. 2002, MNRAS, 333, 383
Forbes, D. A., et al. 2004, MNRAS, 355, 608
Geisler, D. 1996, AJ, 111, 480
Geisler, D., & Forte, J. 1990, ApJ, 350, L5
Geisler, D., Lee, M. G., & Kim, E. 1996, AJ, 111, 1529
Harris, G. L. H., Harris, W. E., & Geisler, D. 2004, AJ, 128, 723
Harris, H. C., & Canterna, R. 1977, AJ, 82, 798
Harris, W. E. 1996, AJ, 112, 1487
Harris, W. E., Allwright, J. W. B., Pritchet, C. J., & van den Bergh, S. 1991, ApJS, 76, 115
Harris, W. E., & Harris, G. L. H. 2002, AJ, 123, 3108
Harris, W. E., Harris, G. L. H., & McLaughlin, D. E. 1998, AJ, 115, 1801
Harris, W. E., Whitmore, B. C., Karakla, D., Okoni, W., Baum, W. A., Hanes, D. A., & Kavelaars, J. 2006, ApJ, 636, 90
Humphrey, P. J., Boute, D. A., Gaskell, D., Zappacosta, L., Bullock, J. S., Brightenti, F., & Mathews, W. G. 2006, ApJ, 646, 899
Hwang, H. S., et al. 2008, ApJ, 674, 869
Jordan, A., et al. 2007, ApJS, 171, 101
Kim, E., Kim, D.-W., Fabbiano, G., Lee, M. G., Park, H. S., & Geisler, D., & Dirsch, B. 2006, ApJ, 657, 276
King, I. 1962, AJ, 67, 471
Kissler-Patig, M., Brodie, J. P., Schroder, L. L., Forbes, D. A., Grillmair, C. J., & Huchra, J. P. 1998, AJ, 115, 105
Koopman, R. A., Kenney, J. D. P., & Young, J. 2001, ApJS, 135, 125
Kratzov, A. V., & Gnedin, O. Y. 2005, ApJ, 623, 650
Kron, R. 1980, ApJS, 43, 493
Lee, M. G., & Kim, E. 1996, AJ, 111, 1529
Lee, M. G., & Kim, D.-W., Fabbiano, G., Lee, M. G., Park, H. S., Geisler, D., & Dirsch, B. 2006, ApJ, 647, 276
Lee, M. G., et al. 2008, ApJ, 674, 869
Lee, M. G., & Geisler, D. 1993, AJ, 106, 493
Lee, M. G., & Kim, E. 2000, ApJ, 592, 866
Lee, M. G., Harris, G. L. H., & McLaughlin, D. E. 1998, AJ, 115, 1801
Lee, M. G., et al. 2004, MNRAS, 355, 608
Mei, S., et al. 2007, ApJ, 655, 144
Mieske, S., et al. 2006, ApJ, 653, 193
Miller, B. 2006, preprint (astro-ph/0606062)
Neilsen, E. H., Jr. 1999, Ph.D. thesis, Johns Hopkins Univ.
O'Sullivan, E., Forbes, D. A., & Ponman, T. J. 2001, MNRAS, 328, 461
Peebles, P. J. E., & Dicke, J. H. 1968, ApJ, 154, 891
Peletier, R. F., Davies, R. L., Illingworth, G. D., Davis, L. E., & Cowton, M. 1990, AJ, 100, 1091
Peng, E. W., et al. 2006, ApJ, 639, 95
Pierce, M., et al. 2006, MNRAS, 368, 325
Pinkney, J., et al. 2003, ApJ, 596, 903
Randall, S. W., Sarazin, C. L., & Irwin, J. A. 2004, ApJ, 600, 729
Randall, S. W., Sarazin, C. L., & Irwin, J. A. 2006, ApJ, 636, 200
Rhode, K. L., & Zepf, S. E. 2001, AJ, 121, 210
———. 2004, AJ, 127, 302
Sandage, A., & Bedke, J. 1994, The Carnegie Atlas of Galaxies (Washington: Carnegie Inst.)
Sarazin, C., Kundu, A., Irwin, J. A., Sivakoff, G. R., Blanton, E. L., & Randall, S. W. 2003, ApJ, 595, 743
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Strader, J., Brodie, J. P., & Beasley, M. A. 2007, AJ, 133, 2015
Strader, J., Brodie, J. P., Spitler, L., & Beasley, M. A. 2006, AJ, 132, 2333
Stetson, P. B. 1994, PASP, 106, 250
Tamura, N., Sharples, R. M., Arimoto, N., Onodera, M., Ohta, K., & Yamada, Y. 2006a, MNRAS, 373, 588
———. 2006b, MNRAS, 373, 601
Thoul, A., Jorissen, A., Goriely, S., Jehin, E., Magain, P., Noels, A., & Parmentier, G. 2002, A&A, 383, 491
Trumpler, R. J., & Weaver, H. F. 1953, Statistical Astronomy (Berkeley: Univ. California Press)
Web, M. J. 1993, MNRAS, 265, 755
White, R. E., III, Keel, W. C., & Conceix, C. J. 2000, ApJ, 542, 761
Yoon, S.-J., Yi, S. K., & Lee, Y.-W. 2006, Science, 311, 1129