THE GLOBULAR CLUSTER SYSTEM OF M60 (NGC 4649). II. KINEMATICS OF THE GLOBULAR CLUSTER SYSTEM

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ABSTRACT

We present a kinematic analysis of the globular cluster (GC) system in the giant elliptical galaxy (gE) M60 in the Virgo Cluster, using a photometric and spectroscopic database of 121 GCs (83 blue and 38 red GCs). We have found that the M60 GC system shows a significant overall rotation. The rotation amplitude of the blue GCs is slightly smaller than or similar to that of the red GCs, and the position angles of their rotation axes are similar. The velocity dispersions about the mean velocity and about the best-fit rotation curve for the red GCs are marginally larger than those for the blue GCs. Comparison of observed stellar and GC velocity dispersion profiles with those calculated from the stellar mass profile shows that the mass-to-light ratio should increase as the galactocentric distance increases, indicating the existence of an extended dark matter halo. The sample of all the GCs in M60 is found to have a tangentially biased velocity ellipsoid, unlike the GC systems in other gEs. The two subsamples appear to have different velocity ellipsoids. The blue GC system has a modestly tangentially biased velocity ellipsoid, while the red GC system has a modestly radially biased or an isotropic velocity ellipsoid. We compare the kinematic properties of the M60 GC system to those of other gEs (M87, M49, NGC 1399, NGC 5128, and NGC 4636), and discuss the implication of these results for the formation models of the GC system in gEs.

Subject headings: galaxies: clusters: general — galaxies: individual (M60) — galaxies: kinematics and dynamics — galaxies: star clusters

Online material: color figures

1. INTRODUCTION

Globular clusters (GCs) have long been recognized as an important tracer for understanding the formation and evolution of galaxies. To solve the mystery of galaxy formation and evolution, several of the GCs' photometric properties, such as color distribution, spatial structure, and luminosity function, have been used (Lee 2003; West et al. 2004; Brodie & Strader 2006). However, it is still difficult to test the predictions of the formation models of galaxies and their GC systems using photometric data alone.

Recently, with the aid of large telescopes with apertures larger than 4 m, a large sample (N > 150) of GC spectra for one galaxy has been obtained, which can be used for statistically meaningful kinematic studies (e.g., Côté et al. 2001, 2003; Richtler et al. 2004; Peng et al. 2004). Due to their wide spatial distribution, brightness, and compact size, GCs are useful test particles for tracing the gravitational potential of their host galaxies, and especially of the dark matter halo beyond several effective radii of the galaxy. Therefore, a kinematic study of the GC system enables us to estimate the global mass distribution of the GCs' host galaxy, or to constrain the orbital properties of GCs using an independently determined mass profile (e.g., from X-ray emission) of the galaxy. Moreover, the kinematic difference between GC subpopulations (blue and red GCs) can be used as an observational constraint on the galaxy formation model.

To date, we know of six giant elliptical galaxies (gEs) for which the kinematics of the GC system have been studied: M87 (Cohen & Ryzhov 1997; Kissler-Patig & Gebhardt 1998; Côté et al. 2001), M49 (Zepf et al. 2000; Côté et al. 2003), NGC 1399 (Kissler-Patig et al. 1998, 1999; Minniti et al. 1998; Richtler et al. 2004), NGC 5128 (Peng et al. 2004; Woodley et al. 2007), NGC 4636 (Schuberth et al. 2006), and M60 (Bridges et al. 2006). M87, a cD galaxy of the Virgo cluster, was recently studied by Côté et al. (2001) using ∼280 velocity data points of GCs. The velocity dispersions of the blue and red GCs were found to be ∼410 and ∼390 km s⁻¹, respectively. Both the blue and red GCs appear to rotate around the photometric minor axis, with a similar rotation amplitude of ∼160 km s⁻¹ when averaged over the whole system, while the blue GCs appear to rotate around the photometric major axis inside a radius of ∼16 kpc. The system of all the GCs has an isotropic velocity ellipsoid, while the blue and red GC systems show tangentially and radially biased ellipsoids, respectively. Côté et al. (2003) studied the GC kinematics of M49, the brightest member of the Virgo cluster, using ∼260 velocity data points of GCs. They found that the velocity dispersion of the blue GCs (∼350 km s⁻¹) was larger than that of the red GCs (∼270 km s⁻¹). The blue GCs rotate roughly around the photometric axis of M49, with a rotation amplitude of ∼100–150 km s⁻¹, while the red GCs show some evidence of weak rotation (∼50 km s⁻¹) around the same axis, but in a different direction. The combined, blue, and red GC systems appear to have an isotropic velocity ellipsoid. NGC 1399, a cD galaxy of the Fornax cluster, was studied by Richtler et al. (2004) with the largest number (∼470) of GC velocity data points. The velocity
dispersions of the blue and red GCs were estimated to be $\sim 291$ and $\sim 255$ km s$^{-1}$, respectively. No significant rotations were found for either the blue or the red GCs, although there is a weak signature of rotation for blue GCs beyond 6$^\circ$. The velocity anisotropies for both the blue and red GCs are consistent with isotropic orbits. Using $\sim 220$ GC data points of NGC 5128, Peng et al. (2004) found that the red GCs exhibit a significant rotation, while the blue GCs do not show a clear hint of rotation. Later, Woodley et al. (2007), using 340 GC data points for NGC 5128, showed that the rotation amplitude and the velocity dispersions for the subsamples are quite similar. For NGC 4636, Schuberth et al. (2006) found that the velocity dispersions of the blue and red GCs are not different, but the rotation of the red GCs is stronger than that of the blue GCs. In summary, all these GC systems show diverse GC kinematics in velocity dispersion, rotation, and radial variation (see § 4.1), making it difficult to draw any strong conclusion about the uniform formation history of the GC system in gEs.

M60 (NGC 4649) is a giant elliptical galaxy in the Virgo cluster, slightly less luminous than M87 and M49. M60 has a nearby companion Sc galaxy, NGC 4647, located 2.5$^\circ$ from the center of M60. While there were numerous photometric studies of the GC system in M60 based on ground-based images (Couture et al. 1991; Harris et al. 1991; Ashman & Zepf 1998; Forbes et al. 1991), it was difficult to derive the kinematic properties up to several effective radii, and to distinguish the kinematic difference between the blue and red GCs. Using the spectroscopic data of GCs given in Paper I, which was published in 2006, we selected in Paper I. Section 2 gives a brief description of the data set of M60 GCs. In Figure 1, we show the spatial distribution of 121 GCs in M60 using Gemini/GMOS. They found no obvious signs of a recent starburst, interaction, or merger by estimating the ages and metallicities from the spectra of M60 GCs. Later, Bridges et al. (2006) investigated the kinematics of the M60 GC system using the velocity data of Pierce et al. (2006). They reported that the velocity dispersion of the blue GCs is smaller than that of the red GCs, unlike the cases of other gEs. They found no hint of rotation in the GC system of M60. Furthermore, the orbital distribution of the GC system is found to be close to isotropic inside the radius of 100$^\circ$, but becomes tangentially biased beyond this radius. However, due to their small number ($N \approx 38$) of GC velocity data points with limited radial and azimuthal coverage, it was difficult to derive the kinematic properties up to several effective radii, and to distinguish the kinematic difference between the blue and red GCs.

We have carried out a photometric study of the GC system in M60 using deep wide-field CT$^2$H images obtained at the Kitt Peak National Observatory (KPNO) 4 m telescope (Lee et al. 2007), and Hubble Space Telescope (HST) images (Neilsen 1999; Kundu & Whitmore 2001; Larsen et al. 2001; Peng et al. 2006; Strader et al. 2006; Mieske et al. 2006), there were few spectroscopic studies of the M60 GC system (Pierce et al. 2006). Pierce et al. (2006) published the first spectroscopical observational results for 38 GCs (16 blue and 22 red GCs) in M60 using Gemini/GMOS. They found no obvious signs of a recent starburst, interaction, or merger by estimating the ages and metallicities from the spectra of M60 GCs. Later, Bridges et al. (2006) investigated the kinematics of the M60 GC system using the velocity data of Pierce et al. (2006). We selected GC candidates from deep, wide-field Washington C and $T_1$ images ($16' \times 16'$) obtained at the KPNO 4 m telescope (Lee et al. 2007), and F555W ($V$) and F814W ($I$) images from the HST WFPC2 archive data (Neilsen 1999; Kundu & Whitmore 2001; Larsen et al. 2001). Spectroscopic observations were made using the Multi Object Spectrograph (MOS) at the 3.6 m CFHT in 2002 February and in 2003 May for 165 GC candidates with $19 < T_1 < 22$ mag and $1.0 < (C - T_1) < 2.4$. We determined the radial velocities of GC candidates by cross-correlating the candidate spectrum with that of three Galactic GCs. Among 165 GC candidates, we extracted spectra and determined radial velocities for 111 objects, while for 54 objects we were unable to do this due to the poor quality of their spectra. We increased the number of GCs by combining our radial velocity data with those of Pierce et al. (2006). The radial velocities of GCs in Pierce et al. (2006) were transformed into our velocity system using equation (1) in Paper I, and the transformed velocities were used for further analysis. Of the entire spectroscopic sample of GC candidates (110 from the CFHT observation [Paper I] and 38 from Pierce et al. 2006), 121 genuine GCs were selected in Paper I using radial velocities ($500 \leq v_p \leq 1600$ km s$^{-1}$) and colors ($1.0 \leq C - T_1 < 2.4$ mag). There are 83 blue GCs with $1.0 \leq (C - T_1) < 1.7$ and 38 red GCs with $1.7 \leq (C - T_1) < 2.4$ in the total sample. Foreground reddening toward M60 is very small, $E(B - V) = 0.026$ (Schlegel et al. 1998), which corresponds to $E(C - T_1) = 1.966 E(B - V) = 0.051$, $A(T_1) = 0.071$, and $A(V) = 0.088$.

In Figure 1, we show the spatial distribution of 121 GCs in M60 with measured velocities. Two large dotted ellipses represent the major and minor axes of the GC system in M60 based on ground-based images (Couture et al. 2006; Lee et al. 2007) and Hubble Space Telescope (HST) images (Neilsen 1999; Kundu & Whitmore 2001; Larsen et al. 2001; Peng et al. 2006; Strader et al. 2006; Mieske et al. 2006), respectively. The GCs with velocities larger than the systemic velocity ($v_{sys} = 1056$ km s$^{-1}$) of M60 are represented by open symbols, while those with velocities smaller than the systemic velocity of M60 are represented by filled symbols. The symbol size is proportional to the velocity deviation. M60 and its companion galaxy, NGC 4647, are represented by large dotted $D_{25}$ ellipses. The photometric major and minor axes of M60 are represented by the dashed lines. [See the electronic edition of the Journal for a color version of this figure.]

2. DATA

We used the spectroscopic data of GCs given in Paper I, which describes the details of the spectroscopic observation, data reduction, and the data set. Here we only give a brief summary of the data set of M60 GCs.

We selected GC candidates from deep, wide-field Washington C and $T_1$ images ($16' \times 16'$) obtained at the KPNO 4 m telescope (Lee et al. 2007), and F555W ($V$) and F814W ($I$) images from the HST WFPC2 archive data (Neilsen 1999; Kundu & Whitmore 2001; Larsen et al. 2001). Spectroscopic observations were made using the Multi Object Spectrograph (MOS) at the 3.6 m CFHT in 2002 February and in 2003 May for 165 GC candidates with $19 < T_1 < 22$ mag and $1.0 \leq (C - T_1) < 2.4$. We determined the radial velocities of GC candidates by cross-correlating the candidate spectrum with that of three Galactic GCs. Among 165 GC candidates, we extracted spectra and determined radial velocities for 111 objects, while for 54 objects we were unable to do this due to the poor quality of their spectra. We increased the number of GCs by combining our radial velocity data with those of Pierce et al. (2006). The radial velocities of GCs in Pierce et al. (2006) were transformed into our velocity system using equation (1) in Paper I, and the transformed velocities were used for further analysis. Of the entire spectroscopic sample of GC candidates (110 from the CFHT observation [Paper I] and 38 from Pierce et al. 2006), 121 genuine GCs were selected in Paper I using radial velocities ($500 \leq v_p \leq 1600$ km s$^{-1}$) and colors ($1.0 \leq C - T_1 < 2.4$ mag). There are 83 blue GCs with $1.0 \leq (C - T_1) < 1.7$ and 38 red GCs with $1.7 \leq (C - T_1) < 2.4$ in the total sample. Foreground reddening toward M60 is very small, $E(B - V) = 0.026$ (Schlegel et al. 1998), which corresponds to $E(C - T_1) = 1.966 E(B - V) = 0.051$, $A(T_1) = 0.071$, and $A(V) = 0.088$.

In Figure 1, we show the spatial distribution of 121 GCs in M60 with measured velocities. Two large dotted ellipses represent
isophotes at the 25.0 B-mag arcsec$^{-2}$ of M60 (larger ellipse) and NGC 4647 (smaller ellipse) (de Vaucouleurs et al. 1991).

It is worth noting that the majority of high-velocity GCs (open symbols) with velocities larger than the systemic velocity of M60 ($v_{\text{sys}} = 1056 \pm 64$ km s$^{-1}$; Paper I) appear to be located to the northwest of M60. On the other hand, the majority of low-velocity GCs (filled symbols) with velocities smaller than the systemic velocity of M60 appear to be located to the southeast of M60. This might be related to the overall rotation of the M60 GC system around the minor axis. However, a careful analysis is needed for further dynamical investigation, due to the nonuniform spatial coverage of observed genuine GCs around M60.

3. RESULTS

Using the master catalog of 121 GCs in M60 (Paper I), we have investigated the kinematic properties of the M60 GC system: the rotation amplitude, the position angle of the rotation axis, the mean line-of-sight velocity, the projected velocity dispersion, and the velocity ellipsoid.

3.1. Rotation of the Globular Cluster System

A detailed description of the relation between the intrinsic rotational velocity field and the projected one is given in Côté et al. (2001). In summary, if we assume that the GC system is spherically symmetric with an intrinsic angular velocity field stratified on spheres, and that the GC rotation axis lies in the plane of the sky, then we can find that radial velocities of GCs depend sinusoidally on the azimuthal angles. For the M60 GC system, the assumption of spherical symmetry is reasonable due to the modest projected ellipticity (effective ellipticity $e_{\text{eff}} = 0.21$; Lee et al. 2007). Therefore, we fit the observed line-of-sight velocities ($v_p$) of the GCs with the function

$$v_p(\Theta) = v_{\text{sys}} + (\Omega R) \sin(\Theta - \Theta_0),$$

where $\Theta$ is the projected position angle of the GCs relative to the galaxy center measured from north to east, $\Theta_0$ is the projected position angle of the rotation axis of the GC system, $R$ is the projected galactocentric distance, $\Omega R$ is the rotation amplitude, and $v_{\text{sys}}$ is the systemic velocity of the GC system.

In Figure 2, we plot the radial velocities of the GCs with measured uncertainties as a function of position angle for all 121 GCs (top), the 83 blue GCs (middle), and the 38 red GCs (bottom). The best-fit rotation curve of equation (1) for each sample is overlaid. The fitting was done using an error-weighted, nonlinear fit of equation (1), with $v_{\text{sys}}$ as a fixed value of M60 recession velocity ($v_{\text{sys}} = 1056 \pm 64$ km s$^{-1}$) rather than as a free parameter for a better fitting. Using the biweight location of Beers et al. (1990), the systemic velocity of the M60 GC system is estimated to be $v_{\text{sys}} = 1073^{+26}_{-23}$ km s$^{-1}$ (see § 3.2), which agrees with the M60 recession velocity (1056 $\pm$ 64 km s$^{-1}$) and the biweight mean velocity (1066 $\pm$ 45 km s$^{-1}$) for the 38 GCs given by Bridges et al. (2006) within the uncertainty. We derived the rotation amplitudes, $\Omega R$, as $141^{+38}_{-34}$ km s$^{-1}$ for all the GCs, $130^{+65}_{-56}$ km s$^{-1}$ for the blue GCs, and $171^{+58}_{-45}$ km s$^{-1}$ for the red GCs. Thus, the rotation amplitude of the blue GCs is slightly smaller than that of the red GCs, or is consistent with that of the red GCs within the uncertainty. Our results based on all 121 GCs are in contrast to Bridges et al. (2006), who found no rotation using only 38 GCs. To investigate the cause of the difference in the rotation amplitudes between our study and Bridges et al. (2006), we estimated the rotation amplitude using all 121 GCs by dividing the GCs into 54 GCs that were within the region of Bridges et al. (2006) and 67 GCs that were outside it. In the result, the rotation amplitude of the former sample was estimated to be $74^{+30}_{-20}$ km s$^{-1}$, which was much smaller than that of the latter sample ($\Omega R = 221^{+44}_{-31}$ km s$^{-1}$). Therefore, we conclude that the lack of rotation found in Bridges et al. (2006) is because of the small spatial coverage of their study.

In addition, we estimate the orientation of the rotation axis ($\Theta_0$) to be $222^\circ^{+12}_{-14}$ for all the GCs, $218^\circ^{+16}_{-19}$ for the blue GCs, and $237^\circ^{+18}_{-19}$ for the red GCs. The orientations of the rotation axes for all subsamples appear to be similar, and they are closer to the photometric minor axis ($\Theta_{\text{phot}} = 15^\circ$ or $195^\circ$; Lee et al. 2007) than the photometric major axis. Interestingly, the position angle of NGC 4647 relative to M60 is $314^\circ$ from north to east. This means that the line connecting M60 and NGC 4647 is nearly perpendicular to the rotation axes of the GC system.

In Figure 3, we present the rotation of the GC system for the samples of different radial bins in order to investigate the radial variation of the rotational properties. The top panel shows the GCs in the range $32^\prime\prime < R < 533^\prime\prime$, while the lower two panels show the GCs for the inner region ($32^\prime\prime < R < 200^\prime\prime$, middle) and the outer region ($200^\prime\prime < R < 533^\prime\prime$, bottom). The same fitting procedure used for the results in Figure 2 was applied for all the GCs, the blue GCs, and the red GCs in each radial bin. The best-fit rotation curves for each sample are overlaid as solid lines (all GCs), dashed lines (blue GCs), and dotted lines (red GCs).

It appears that the orientation of rotation axes for all GC subsamples changes slightly from the inner region to the outer region with a large uncertainty. The change of the rotation axis from the inner region to the outer region for the blue GCs is seen in the cases of M87 (Côté et al. 2001) and of M49 (Côté et al. 2003). The orientation of the rotation axis for the blue GCs in M87 drastically changes from the major axis in the inner region to the minor axis in the outer region. However, the blue GCs in M49 show the opposite change, with the rotation axis changing...
from the minor axis in the inner region to the major axis in the outer region. Due to the limited number of GCs in this study, it is difficult to draw a solid conclusion about the radial change of the rotation axis for the M60 GC system. A larger sample of GCs is needed to further study the change of the rotation axis as a function of the radius.

3.2. Velocity Dispersion of the Globular Cluster System

In Table 1 we summarize the kinematics of the M60 GC system derived in this study. Several kinematic parameters for all the GCs, the blue GCs, and the red GCs are presented for the entire region (32″ ≤ R ≤ 533″), the inner region (32″ ≤ R ≤ 200″), and the outer region (200″ ≤ R ≤ 533″). Column (1) defines the range of the projected radial distance in arcsec from the center of M60 for each region, and column (2) gives the median value of the radial distance in arcsec. The number of GCs in each region is shown in column (3). Columns (4) and (5) represent the mean line-of-sight velocity (the biweight location of Beers et al. 1990) and the velocity dispersion about this mean velocity (the biweight scale of Beers et al. 1990), respectively. The position angle of the rotation axis and the rotation amplitude estimated using equation (1) in each region are given in columns (6) and (7), respectively. Column (8) gives the velocity dispersion about the best-fit rotation curve. Column (9) gives the absolute value of the ratio of the rotation amplitude to the velocity dispersion about the best-fit rotation curve. The uncertainties of these values represent 68% (1σ) confidence intervals, which are determined from the numerical bootstrap procedure following the method of Côté et al. (2001). The estimated velocity dispersion for all 121 GCs (234±13 km s−1) agrees with the value (256 ± 29 km s−1) of Bridges et al. (2006), based on 38 GCs within the uncertainty. In addition, it is found that the velocity dispersion about the mean velocity of the GC system for the red GCs (σ_r = 258±13 km s−1) is marginally larger than that for the blue GCs (σ_b = 223±13 km s−1), which confirms the result of Bridges et al. (2006) with improved statistics. Interestingly, the velocity dispersion about the best-fit rotation curve for the red GCs (σ_r,φ = 240±20 km s−1) is also marginally larger than that for the blue GCs (σ_b,φ = 207±10 km s−1).

In Figure 4, we plot the radial velocities of GCs with measured uncertainties against projected galactocentric distances. The mean radial velocities in two radial bins are overlaid by squares with long horizontal error bars. The velocity dispersion about the mean velocity in each bin is also represented by a vertical error bar. The mean velocities of all samples agree well with the systemic velocity of M60. Both of the velocity dispersions about the mean velocity and about the best-fit rotation curve in the inner region are marginally larger than or comparable to those in the outer region for all three samples (see Table 1).

To investigate the radial variation of the velocity dispersion in detail, we present a smoothed radial profile of velocity dispersions about the mean radial velocity (filled symbols) and about the best-fit rotation curve (open symbols) in Figure 5. We calculate

![Figure 3: Radial velocities vs. position angles for the GCs in the range 32″ ≤ R ≤ 533″ (top), 32″ ≤ R ≤ 200″ (middle), and 200″ ≤ R ≤ 533″ (bottom). Filled circles indicate the blue GCs, while open circles indicate the red GCs. The best-fit rotation curves for all GCs (solid curves), blue GCs (dashed curves), and red GCs (dotted curves) within each region are overlaid. The dot-dashed horizontal line indicates the systemic velocity of M60, and the vertical arrow marks the position angle of the photometric minor axis of M60. [See the electronic edition of the Journal for a color version of this figure.]](image-url)
the velocity dispersion of the GCs lying within a bin with fixed radial width, \( \Delta R = 120'' \approx 10.06 \) kpc, by increasing the bin center by a fixed step width, \( \delta R = 10'' \approx 0.84 \) kpc. We define the radial width and the step width such that the number of GCs per bin exceeds 10, and the calculation stops when the number of GCs in a bin is less than 10. The velocity dispersions about the mean radial velocity of the combined GCs and the blue GCs are nearly constant for the range of radius values. However, velocity dispersions of the red GCs are decreasing in the inner region (\( R \leq 18 \) kpc) and are increasing in the outer region (\( R \geq 18 \) kpc), although the variation is not large. The velocity dispersions about the best-fit rotation curves of all three samples are not different from those about the mean radial velocities.

3.3. Velocity Anisotropy of the Globular Cluster System

If we assume the spherical symmetry of the M60 GC system, we can apply the Jeans equation in the absence of rotation to the dynamical analysis of the GC system. The spherical Jeans equation is

\[
\frac{d}{dr} n_{\text{cl}}(r) \sigma^2_{\text{cl}}(r) + \frac{2 \beta_{\text{cl}}(r)}{r} n_{\text{cl}}(r) \sigma^2_{\text{cl}}(r) = -n_{\text{cl}}(r) \frac{GM_{\text{tot}}(r)}{r^2},
\]

where \( r \) is a three-dimensional radial distance from the galactic center, \( n_{\text{cl}}(r) \) is a three-dimensional density profile of the GC system, \( \sigma_{\text{cl}}(r) \) is a radial component of velocity dispersion, \( \beta_{\text{cl}}(r) \equiv 1 - \sigma^2_{\text{cl}}(r)/\sigma^2_{\phi}(r) \) is a velocity anisotropy, \( G \) is the gravitational constant, and \( M_{\text{tot}}(r) \) is a total gravitating mass contained within a sphere of radius \( r \) (e.g., Binney & Tremaine 1987). The parameter \( \sigma_{\phi}(r) \) is a tangential component of velocity dispersion that is equal to an azimuthal component of the velocity dispersion, \( \sigma_{\theta}(r) \), in a spherical case.

Several studies on the dynamics of the GC system have focused on determining the gravitational mass, \( M_{\text{tot}}(r) \), using the Jeans equation by assuming a simple isotropic orbit with \( \beta_{\text{cl}}(r) = 0 \) (e.g., Cohen & Ryzhov 1997; Minniti et al. 1998; Zepf et al. 2000). However, with the aid of an independent determination of the mass profile of an elliptical galaxy using X-ray data (e.g., Briggs & Mathews 1997; Humphrey et al. 2006 for M60), the velocity anisotropy itself can be investigated (e.g., Romanowsky & Kochanek 2001; Côté et al. 2001, 2003). Following the analysis of the M87 GC system by Côté et al. (2001) and of the M49 GC system by Côté et al. (2003), we derive first the three-dimensional density profile of the GC system, \( n_{\text{cl}}(r) \), and the total mass profile, \( M_{\text{tot}}(r) \). Comparing the velocity dispersion profile (VDP) calculated from the Jeans equation using those inputs with the measured VDP, \( \sigma_p(R) \), we determine the velocity anisotropy of the M60 GC system.

3.3.1. Density Profiles for the GC System

We used the surface number density profiles of M60 GCs in Lee et al. (2007). They derived the surface density profile of M60 GCs by combining the HST WFC2 archive data for the inner region at \( R < 1.5' \), and the KPNO data for the outer region at \( R > 1.5' \). They determined the background levels from the mean surface number density of the point sources at \( 9'-10' \) with the same range of magnitude and color as the GCs in the KPNO images: 1.988 \( \pm \) 0.363 arcmin\(^{-2} \) for all the GCs, 1.790 \( \pm \) 0.344 arcmin\(^{-2} \) for the blue GCs, and 0.199 \( \pm \) 0.115 arcmin\(^{-2} \) for the red GCs. Then they subtracted these background values from the original number counts to produce the radial profiles of the net surface number density of the GCs. Since they selected GCs that are brighter than \( T_1 \approx 23.0 \) mag, the surface number density profile
must be corrected in order to account for the GCs that remain uncounted due to the limiting magnitude. To correct the correction factor, equation (11) in McLaughlin (1999) with $V_{\text{lim},1} = \infty$ was used on the assumption that the GC luminosity function of M60 has a Gaussian shape with a peak at $V \approx 23.8$ mag and a dispersion $\sigma = 1.65$ mag (Kundu & Whitmore 2001). It is found that the surface number density of the bright M60 GCs in Lee et al. (2007) should be multiplied by 2.61 to derive the total surface number density.

We display the total surface number density profiles, $N_d(R)$, for the combined, blue, and red GCs in Figure 6. We fit the surface number density profile with the projection of Navarro et al. (1997), the Navarro-Frenk-White (NFW) density profile, $n_d(r) = n_0(r/b)^{-1}(1+r/b)^{-2}$, and with the projection of one of the galaxy models developed by Dehnen (1993), $n_d(r) = n_0(r/a)^{-7}(1+r/a)^{-3}$. The surface number density profile, $N_d(R)$, is related to the three-dimensional density profile $n_d(r)$ as follows:

$$N_d(R) = 2 \int_0^\infty n_d(r) \frac{r \, dr}{\sqrt{r^2 - R^2}}.$$  

The solid and long-dashed lines represent the projected best-fit curves of the NFW profile and of the Dehnen profile, respectively. The fitting results for the combined (C) GCs, the blue (B) GCs, and the red (R) GCs are summarized as follows:

$$n_d^C(r) = 0.61 \, \text{kpc}^{-3} (r/5.96 \, \text{kpc})^{-1} (1+r/5.96 \, \text{kpc})^{-2},$$
$$n_d^B(r) = 0.52 \, \text{kpc}^{-3} (r/6.07 \, \text{kpc})^{-1} (1+r/6.07 \, \text{kpc})^{-2},$$
$$n_d^R(r) = 0.46 \, \text{kpc}^{-3} (r/4.99 \, \text{kpc})^{-1} (1+r/4.99 \, \text{kpc})^{-2},$$  

for the NFW profile, and

$$n_d^C(r) = 1.42 \, \text{kpc}^{-3} (r/7.97 \, \text{kpc})^{-0.29} (1+r/7.97 \, \text{kpc})^{-3.71},$$
$$n_d^B(r) = 0.57 \, \text{kpc}^{-3} (r/8.75 \, \text{kpc})^{-0.40} (1+r/8.75 \, \text{kpc})^{-3.60},$$
$$n_d^R(r) = 0.53 \, \text{kpc}^{-3} (r/8.36 \, \text{kpc})^{-0.56} (1+r/8.36 \, \text{kpc})^{-3.44},$$  

for the Dehnen profile.

It is found that the scale length $b$ of the red GCs in the NFW profile is smaller than that of the blue GCs, indicating that the red GCs are more concentrated toward the galaxy center than the blue GCs, as shown previously (Forbes et al. 2004; Lee et al. 2007).

3.3.2. Need for an Extended Dark Matter Halo in M60

In Figure 7 (left), we plot the surface-brightness profile of M60 as derived from our KPNO $T_1$-band images (Lee et al. 2007) compared to that in Peletier et al. (1990) for R-band photometry. We convert the $T_1$ photometry of Lee et al. (2007) to Cousins R-band photometry using the relation given by Geisler (1996). It is seen that the two profiles agree well over the radius.

We fit the surface-brightness profile derived from the KPNO images (Kim et al. 2006; Lee et al. 2007) with the projection of the three-dimensional luminosity density profile used in Côté et al. (2003), which is represented by

$$j(r) = \frac{(3-\gamma)(7-2\gamma)}{4 \pi a^3} \frac{L_{\text{tot}}}{\left(\frac{r}{a}\right)^{\gamma}} \left[1 + \left(\frac{r}{a}\right)^{1/2}\right]^{2(\gamma-4)}.$$  

The fit yields parameters of $\gamma = 0.32$, $L_{\text{tot}} = 1.32 \times 10^{11} L_{\odot}$, and $a = 1.48$ kpc, and the projected best-fit curve is overlaid in Figure 7. The fitted model also gives an effective radius of $R_{\text{eff}} = 1.96' \simeq 9.86$ kpc, which is slightly larger than that from a fit ($R_{\text{eff}} = 1.83' \simeq 9.23$ kpc at the $T_1$ band) using a de Vaucouleurs law in Lee et al. (2007).

In Figure 7 (right), we show a three-dimensional stellar mass density profile, $\rho_s(r) = \Upsilon_0 j(r)$, with an R-band mass-to-light ratio

![Fig. 6.—Projected number density profiles for all GC candidates (top), the blue GC candidates (middle), and the red GC candidates (bottom). Filled circles represent the GC candidates from the HST WFPC2 archive, while open squares represent the GC candidates from the KPNO CT1 images (Lee et al. 2007). The solid line and the dashed line in each panel indicate the projected best fits using the NFW density profile and the Dehnen density profile, respectively, for each sample. See the electronic edition of the Journal for a color version of this figure.]

![Fig. 7.—Left: R-band surface photometry of M60 derived from KPNO images (open circles; Lee et al. 2007; Kim et al. 2006) compared to that in Peletier et al. (1990; filled circles). The dashed line indicates a projected best fit using eq. (6). Right: Three-dimensional stellar mass density profile using the best-fit model in the left panel with a constant R-band mass-to-light ratio of $\Upsilon_0 = 6.0 \, M_\odot \, L_\odot^{-1}$.]

\( \Theta_0 = 6.0 \, M_{\odot} \, L_{\odot}^{-1} \) (discussed later in this section). Thus we obtain a stellar mass profile of M60, which is represented by

\[
M_*(r) = \int_0^r 4\pi x^2 \rho_*(r) \, dx = \Theta_0 \int_0^r 4\pi x^2 j(x) \, dx
\]

\[
= \Theta_0 L_{\text{tot}} \left[ \frac{(r/a)^{1/2}}{1 + (r/a)^{1/2}} \right]^{\frac{2(1-\gamma)}{3}} \left[ \frac{(7 - 2\gamma) + (r/a)^{1/2}}{1 + (r/a)^{1/2}} \right].
\]

(7)

We used this stellar mass profile to determine the velocity anisotropy for the M60 stellar system and to test the existence of an extended dark matter halo. If we take \( M_{\text{gal}}(r) = M_*(r) \), and substitute \( \rho_*(r) \propto j(r) \) for \( n_g(r) \), then we can compute the intrinsic radial VDP of the stars through the Jeans equation by assuming several R-band mass-to-light ratios (\( \Theta_0 \)) and velocity anisotropies of the stellar system [\( \beta_*(r) \)]. We therefore predict the projected VDPs for the stellar system from the intrinsic radial VDP calculated using equation (10). In Figure 8, we show the projected VDPs calculated with \( \Theta_0 = 6.0 \, M_{\odot} \, L_{\odot}^{-1} \) and \( \beta_*(r) = +0.6 \) (radially biased), which is the best-fit curve for the stellar kinematic data of Fisher et al. (1995), de Bruyne et al. (2001), and Pinkney et al. (2003). This R-band mass-to-light ratio and radially biased velocity anisotropy for the stellar system is similarly found in the M49 stellar system with \( \Theta_0 = 5.9 \, M_{\odot} \, L_{\odot}^{-1} \) and \( \beta_*(r) = +0.3 \) (Côté et al. 2003, and references therein).

For comparison, we also present in Figure 8 the projected VDPs calculated using the same stellar mass profile as above, but for the GC number density profile \( n_g(r) \) and for \( \beta_g(r) = +0.99 \) (radially biased; upper long-dashed lines), \(-0.99\) (tangentially biased; lower long-dashed lines), 0.0 (isotropic; solid line for the NFW profile and short-dashed line for the Dehnen profile). Interestingly, none of these models can account for the observed VDPs for the GCs at \( R > 7 \) kpc, indicating that mass-to-light ratio is not constant over the galactocentric distance, but should increase as the distance increases. This means that there exists an extended dark matter halo in M60.

This result is consistent with the previous findings of an extended dark matter halo in M60 from a radial profile of an increasing mass-to-light ratio in the K band (Humphrey et al. 2006) and in the V band (Bridges et al. 2006) at \( 7 \leq R \leq 22 \) kpc.

### 3.3.3. X-Ray Mass Profile

The total gravitating mass profile is determined using a gas temperature profile and a density distribution obtained from X-ray observational data on the assumption of hydrostatic equilibrium (neglecting the magnetic pressure term):

\[
M_{\text{gal}}(r) = \frac{kT(r) \, \mathcal{G} \mu m_p}{\mu m_p} \left[ \frac{d \log \rho}{d \log r} + \frac{d \log T(r)}{d \log r} \right].
\]

(8)

where \( k \) is the Boltzmann constant, \( G \) is the gravitational constant, \( T(r) \) is the gas temperature at radius \( r \), \( \mu \) is the mean molecular weight (taken as 0.63 in this study), \( m_p \) is the proton mass, and \( \rho(r) \) is the gas density at radius \( r \). For the case of M60, Brigenti & Mathews (1997) derived the total mass profile using Einstein High Resolution Imager observational data of Trinchieri et al. (1986) and ROSAT PSPC observational data of Trinchieri et al. (1997), and Humphrey et al. (2006) derived the total mass profile using Chandra observational data. In addition, Randall et al. (2006) reported the density and the temperature distribution of M60 using XMM-Newton data. Since the derived VDP is sensitive to the mass profile, we estimate mass profiles using these different X-ray data sets.

In Figure 9, we display the deprojected profiles of the gas temperature (top) and the gas number densities (middle and bottom) found by Trinchieri et al. (1986; filled circles), Trinchieri et al. (1997; open circles), Randall et al. (2006; open triangles), and Humphrey et al. (2006; open stars) with measured errors. Having done this, we fit the temperature and gas number density data of each reference using a temperature distribution of \( T(r) = 2T_m [r/r_m + r_o/r_m]^{3\gamma} \), and a density distribution of \( n(r) = \Sigma n_i(r) \), where \( n_i(r) = n_0(i) \{1 + [r/r_0(i)]^{\beta(i)}\}^{-1} \), and \( T_m, r_m, r_o, n_0(i), r_0(i), \) and \( \beta(i) \) are parameters of the fit. We fit the gas number density profile of each data set for cases where \( i \leq 1 \) (a one-component fit) and \( i \leq 2 \) (a two-component fit). The data used are annotated with the associated lines. The results of the fit are summarized in Table 2.

The resulting mass profiles, \( M(r) \), of M60 are presented in Figure 10 for several temperature and gas number density profiles. The upper panel shows the mass profiles using a one-component fit of the gas number density for various data sets. The lower panel shows those using two components of the gas number density for various data sets, and using the mass profile derived by Humphrey et al. (2006) in comparison. It appears that most mass profiles agree well. However, the mass profile derived using the temperature and the gas number density data (with a one-component fit) of Trinchieri et al. (1997) (top panel, dotted line) deviates from the other profiles in the inner region (\( r \leq 10 \) kpc). In addition, the mass profile derived by Humphrey et al. (2006) (bottom panel, short-dashed line) deviates from the other profiles in the region of \( r \leq 1 \) kpc. Comparing X-ray mass profiles with the stellar mass profile (thick solid line) determined in § 3.3.2, we find that most X-ray mass profiles deviate significantly.
from the stellar mass profiles in the inner region at $r < 2$ kpc, indicating that X-ray mass profiles are not reliable at very small radii because of angular resolution limit and nonequilibrium energetics. In the intermediate region at $2 < r < 10$ kpc, the X-ray mass profiles derived using a two-component fit of the gas number density (bottom) agree with the stellar mass profiles, while those derived using a one-component fit of the gas number density (top) do not. In the outer region at $r > 10$ kpc, all X-ray mass profiles are larger than the stellar mass profiles, confirming the need of an extended dark matter halo, as shown in § 3.3.2. Since the discrepancy between X-ray and stellar mass profiles is significant only in the inner region at $r < 2$ kpc, where there are no GCs, and since X-ray mass profiles that account for the dark matter halo are similar to, or larger than, the stellar mass profile at $r > 2$ kpc, we conclude that the X-ray mass profiles are good enough to determine the velocity anisotropy of the M60 GC system for the following analysis.

3.3.4. Determination of the Velocity Anisotropy

We determine the velocity anisotropy of GCs as follows: (1) with the GC number density profile $n_G(r)$ of the combined, blue, and red GCs, and the mass profile $M_{\text{tot}}(r)$ in hand, assuming the velocity anisotropy $\beta(r)$ in prior, we derive the theoretical projected VDP $\sigma_p(R)$ and theoretical projected aperture VDP $\sigma_{ap}(\leq R)$ using the Jeans equation; (2) from the comparison of these calculated VDPs with measured VDPs, we determine the velocity anisotropy of GCs.

We begin by deriving the theoretical projected VDPs. The spherical Jeans equation (eq. [2]) can be solved for the radial component of velocity dispersion, $\sigma_r(r)$:

$$\sigma_r(r) = \frac{1}{n_G(r)} \exp\left(-\int \frac{2\beta \, dr}{r}\right) \times \left[\int_0^\infty n_G \frac{GM_{\text{tot}}}{x^2} \exp\left(\int \frac{2\beta \, dx}{x}\right) \, dx\right].$$  \hspace{1cm} (9)

Then the projected VDP, $\sigma_p(R)$, can be derived by

$$\sigma_p^2(R) = \frac{2}{N_G(R)} \int_0^R n_G \sigma_r^2(r) \left(1 - \frac{R^2}{r^2}\right) \, \frac{r \, dr}{\sqrt{r^2 - R^2}},$$  \hspace{1cm} (10)

where $R$ is the projected galactocentric distance, and the surface density profile, $N_G(R)$, is a projection of the three-dimensional density profile $n_G(r)$.

The projected aperture VDP, $\sigma_{ap}(\leq R)$, which is the velocity dispersion of all objects within a given projected radial distance $R$, can be computed by

$$\sigma_{ap}^2(\leq R) = \left[\int_{R_{\text{min}}}^R N_G(R) \sigma_p^2(R) \, dR'\right]^{-1},$$  \hspace{1cm} (11)

where $R_{\text{min}}$ is the projected galactocentric distance of the innermost data point in the GC sample ($R_{\text{min}} = 2.7$ kpc in this study).

We present the measured VDP in comparison with the VDPs calculated by assuming several velocity anisotropies in Figures 11 and 12. Figure 11 shows the VDPs calculated using the Dehnen profile for the GC number density, while Figure 12 shows those calculated using the NFW profile for the GC number density.

### Table 2

| Data      | $T_\text{e}$ (10^7 K) | $r_\text{in}$ (kpc) | $r_\text{out}$ (kpc) | $\beta$ | $n_G(1)$ (cm^{-3}) | $r_G(1)$ (kpc) | $p(1)$ | $n_G(2)$ (cm^{-3}) | $r_G(2)$ (kpc) | $p(1)$, $p(2)$ |
|-----------|-----------------------|---------------------|----------------------|--------|-------------------|----------------|-------|-------------------|----------------|--------------|
| T97^a      | 1.16                  | 37.32               | 23.03                | -0.003 | 0.02              | 2.60           | 1.45  | ...               | ...            | ...          |
| T97+T86^b  | ...                   | ...                 | ...                  | ...    | 0.09              | 0.70           | 1.41  | 0.07, 0.0009      | 0.97, 16.83    | 1.69, 2.22  |
| R06^c      | 7.47                  | 19.49               | 17.34                | 0.19   | 0.14              | 0.81           | 1.65  | 0.06, 0.05        | 0.81, 1.61     | 3.08, 1.71  |
| BM97^d     | 0.9                   | 24.28               | 24.28                | 0.0    | 0.1               | 0.9            | 18.21 | 1.8               | 3.0            | ...          |

^a Trinchieri et al. (1997).

^b Trinchieri et al. (1997, 1986).

^c Randall et al. (2006).

^d Values taken from Brighenti & Mathews (1997).
The top panels show the projected VDPs, and the bottom panels show the projected aperture VDPs. The measured dispersion data taken from Figure 5 are shown by filled circles, along with their confidence intervals. The projected aperture VDPs in the bottom panels are plotted in a fashion similar to that of the top panel. The calculated VDPs in the left panels are obtained with mass profiles derived using a one-component fit of the gas number density, while those in the right panels are obtained with mass profiles derived using a two-component fit. Although it is difficult to clearly distinguish the velocity anisotropy for nearly all radial distances in the top panels (the bottom panels show a more consistent with those of Bridges et al. (2006) as a whole, although the signature of an isotropic orbit within 100″ is weaker in this study. However, we extend the radial coverage (≈21 kpc) of Bridges et al. (2006) out to 40 kpc in this study.

In Figures 13 and 14, we show a similar analysis for the blue and red GCs, respectively. We present the results using the Dehnen profile for GC number density. In Figures 13 and 14, it is not easy to draw a strong conclusion due to the small number statistics and complex mass profiles, we note a difference of velocity ellipsoids between the blue and red GCs in the projected aperture VDP (Figs. 13 and 14, bottom). It appears that the blue GC system has a tangentially biased velocity ellipsoid with $\beta_2 < 0$, while the red GC system has a radially biased, or an isotropic velocity ellipsoid.

4. DISCUSSION

4.1. Comparison with the GC Systems in Other gEs

To date, the kinematics of the GC systems of five giant elliptical galaxies apart from M60 have been studied: M87 (Cohen & Ryzhov 1997; Kisser-Patig & Gebhardt 1998; Côte et al. 2001), M49 (Zepf et al. 2000; Côte et al. 2003), NGC 1399 (Kisser-Patig et al. 1998, 1999; Minniti et al. 1998; Richtler et al. 2004), NGC 5128 (Peng et al. 2004; Woodley et al. 2007), and NGC 4636 (Schuberth et al. 2006).

For the comparison of the kinematic properties of the GCs in those gEs, we analyze the velocity data of 276 GCs in M87 (Côte et al. 2001), 263 GCs in M49 (Côte et al. 2003), 435 GCs in NGC 1399 (Richtler et al. 2004), 210 GCs in NGC 5128 (Peng et al. 2004), and 172 GCs in NGC 4636 (Schuberth et al. 2006) using a method similar to the one adopted in this study. M87, M49, and NGC 4636, as well as M60, are gEs in the Virgo cluster, and NGC 1399 is a gE in the Fornax cluster at a distance similar to that of the Virgo cluster. NGC 5128, the nearest gE, is in the Centaurus group. The basic photometric properties of these galaxies are listed in Table 3. Columns (1), (2), and (3) give the name of the galaxy, the absolute magnitude in the $V$ band, and the systemic radial velocity, respectively. The effective radius, the ellipticity, the position angle of the photometric minor axis in degrees east of north, and the distance are shown in columns (4), (5), (6), and (7), respectively. The resulting global kinematics for the combined, blue, and red GCs of each galaxy are presented in Table 4. These are the mean radial velocity, the velocity dispersion about the mean radial velocity, the rotation axis, the rotation amplitude, the rotation-corrected velocity dispersion, and the absolute value of the ratio of the rotation amplitude to the velocity dispersion about the best-fit sine curve for each GC subsample.

For the kinematic analysis, we divide the GCs in each gE into blue and red GCs using the colors that were used in the associated reference, excluding the GCs without color information. In addition, we estimate the rotation amplitude and the position angle of the rotation axis for the GC system of NGC 5128 by fitting the mean velocity of the GCs lying within a fixed width (60°) of the position angle for a stable computation. The velocity dispersions derived in this study agree well with those derived in the associated reference. The velocity dispersions of GCs in M87 ($\sigma_p = 414\pm16$ km s$^{-1}$) and NGC 1399 ($\sigma_p = 323\pm11$ km s$^{-1}$) are found to be larger than, and comparable to, that of the GCs in M49 ($\sigma_p = 322\pm14$ km s$^{-1}$), respectively, although M87 and NGC 1399 are fainter than M49. This is due to the fact that M87 and NGC 1399 are located in the center of a galaxy cluster, while M49 is not. NGC 5128 shows the smallest velocity dispersion ($\sigma_p = 129\pm5$ km s$^{-1}$) among our sample galaxies, implying a relatively smaller mass in spite of its high luminosity in the $B$ band ($M_B = -21.7$).

Table 5 lists several notable features based on the global kinematics presented in Table 4. The strength of the rotation is defined in column (4): strong for $\Omega_R/\sigma_p > 0.4$, modest for $0.4 \leq \Omega_R/\sigma_p < 0.2$, and weak for $\Omega_R/\sigma_p < 0.2$. The rotation axis in column (5) is assigned if the difference between the position angle of the rotation axis and that of the photometric major/minor axis is less than 30°. The result of velocity anisotropy for each GC system is taken from the literature (see col. [6]). It appears that the rotation-corrected velocity dispersion, $\sigma_{p, r}$, of the blue GCs is similar to, or larger than, that of the red GCs, except for M60. This implies that the blue GC system is dynamically...
hotter than the red GC system in most gEs. However, the case of rotation ($\Omega R/\sigma_p$) is not simple. Both the blue and red GCs in M60 and M87 show strong rotation, while those in NGC 1399 show weak rotation. The red GCs in NGC 4636 and NGC 5128 show slightly stronger rotation than the blue GCs. However, the red GCs in M49 show weak rotation, while the blue GCs show modest rotation, which is consistent with the prediction of the merger formation model (Ashman & Zepf 1992). In addition, if we consider the position angle of the rotation axis as well, the story becomes more complicated. In velocity anisotropy, it appears that the samples of all the GC systems in three gEs (M87, M49, and NGC 1399) have an isotropic velocity ellipsoid, and that the two subsamples have different velocity ellipsoids in two gEs (M60 and M87). It is necessary to determine the velocity anisotropy of the GC systems in more gEs, including NGC 5128 and NGC 4636.

To examine the general kinematic properties of the GC systems in gEs, we plot the rotation-corrected velocity dispersions in gEs against the projected galactocentric distances in Figure 15. The rotation-corrected velocity dispersion is normalized by that...
of all the GCs in each gE. The projected galactocentric distance is normalized by the effective radius of each gE. The combined and blue GCs do not show a significant change in velocity dispersion over the whole region of a galaxy. However, the velocity dispersion of the red GCs in the inner region ($R < 2R_{\text{eff}}$) is, on average, marginally larger than that in the outer region ($R > 2R_{\text{eff}}$). This implies that the red GC system in the inner region may be dynamically hotter than that in the outer region. In Figure 16, the absolute value of the ratio of the rotation amplitude to the velocity dispersion is plotted as a function of the projected galactocentric distance. For the red GCs, the ratio of the rotation amplitude to the velocity dispersion in the outer region appears to be marginally larger than that in the inner region if we neglect NGC 4636 (filled pentagon), although it does not change with the distance for the combined and blue GCs.

In summary, differences in kinematic properties among GC subsamples appear to exist, although it depends on the galaxy. The blue GC system appears to be dynamically similar to, or hotter than, the red GC system, and the rotation of the GC system is not negligible. The sample of all GCs in each GC system appears to have an isotropic velocity ellipsoid, while the red GC and blue GC subsamples do not show unified velocity anisotropy. The kinematic properties of M60 and M87 are similar except for the velocity dispersion of their subsamples and the velocity anisotropy of the combined GC system, while other galaxies have diverse kinematic properties. For the red GCs, the velocity dispersion of
the inner region is marginally larger than that of the outer region, while the rotation of the outer region appears to be more significant than that of the inner region.

4.2. Formation Models of Globular Clusters

The kinematic properties of the GC system in M60 compared to those in other gEs are useful for testing the kinematic predictions of formation models of the GCs in a gE. A summary of several model descriptions and predictions can be found in several papers (Rhode & Zepf 2001; Lee 2003; Richtler et al. 2004; West et al. 2004; Brodie & Strader 2006). Classical formation models can be divided into four broad categories: the monolithic collapse model, the major merger model, the multiphase dissipational collapse model, and the dissipationless accretion model.

According to the monolithic collapse model, an elliptical galaxy and its GCs are formed through the collapse of an isolated massive gas cloud or protogalaxy at high redshift (Larson 1975; Carlberg 1984; Arimoto & Yoshii 1987). In this model, the color distribution of the GCs shows a smooth shape with a single peak, and the rotation of the GCs can be generated by tidal torques from companions (Peebles 1969). Although this model can explain some observational properties of elliptical galaxies successfully (see Chiosi & Carraro 2002), the bimodal color distribution of the GC system in many gEs (e.g., Lee 2003; Peng et al. 2006) make it hard to accept this model. In addition, the strong rotation of the GC system as seen in M60 and M87 is not expected from the collapse of a single, isolated protogalactic cloud. Moreover, several GC systems in gEs show a globally isotropic velocity...
ellipsoid that needs some kind of relaxation processes that the monolithic collapse model cannot account for.

The major merger model suggests that elliptical galaxies are formed by a merger of two or more disk galaxies (Toomre 1977; Ashman & Zepf 1992; Zepf et al. 2000). In this model, younger, spatially concentrated, red GCs are formed during the merger, while spatially extended, blue GCs come from the halos of the disk galaxies (e.g., Bekki et al. 2002). As a result, the color distribution of the GCs is expected to be bimodal. This model predicts that the newly formed red GCs will show little rotation compared to the blue GCs, since the angular momentum will be transported to the outer region during the merging process. This model has received particular attention, since it could explain several photometric properties of the GC system in gEs and the weak rotation of the red GC system in M49 (Zepf et al. 2000). However, contrary to the case of M49, the red GC systems in M60, M87, NGC 5128, and NGC 4636 show strong or modest rotation. From the simulation of dissipationless major mergers of spiral galaxies, Bekki et al. (2005) found that both pre-existing metal-poor clusters (MPCs) and metal-rich clusters (MRCs) obtain significant amounts of rotation beyond ~10 kpc, regardless of the orbital configuration of the merging galaxies. However, both the blue and red GC systems in NGC 1399 show weak rotation, which is not consistent with the result of Bekki et al. (2005). Therefore, it is necessary to explain what creates the complex rotational properties of the GC systems in gEs. In the

![Figure 14](image-url)
neighboring galaxies or the accretion from dwarf galaxies. Since star formation phases through a dissipational collapse. In addition, it is difficult to trace the orbital history of the GC system from the galactocentric distance increases up to 90", the stellar velocity dispersion in M60 approaches 200 km s$^{-1}$ (de Bruyne et al. 2001), which is comparable to, or smaller than, the velocity dispersion of the blue GCs. This might support this model, as Forbes et al. (1997) pointed out in the case of NGC 1399 and M87. However, this model disagrees with the result that blue GC systems in several gEs, including M60 in Table 5, exhibit a rotation amplitude larger than or comparable to that of the red GC system.

Côté et al. (1998) proposed the dissipationless accretion model; this model suggests that the red GCs formed in a dissipational collapse, while the blue GCs were subsequently captured from other galaxies through mergers or tidal stripping. It predicts a bimodal color distribution of GCs in gEs and a uniform color distribution in dwarf ellipticals. However, there is an example of a low-luminosity elliptical galaxy (NGC 1427) that shows a bimodal color distribution (Forte et al. 2001). Since the blue GCs are captured from other galaxies, they are expected to show extended spatial distribution. Richtler et al. (2004) argued that if the scenario of Côté et al. (1998) is correct, then the blue GCs should be expected to have radially biased orbits rather than isotropic or tangentially biased orbits, and should also be expected to show no rotation. Although the kinematic data for the outer GCs are not complete to date, current data for the blue GCs in Table 5 show negligible rotation and no signs of radially biased orbits, which is not consistent with the scenario of Côté et al. (1998).

Since the classical models do not give quantitative predictions concerning the kinematic properties of GC systems, it is instructive to compare observational results with those in recent numerical simulations. Although there are some numerical simulations of GC systems that focus on the color distribution (Beasley et al. 2002), the spatial distribution (Moore et al. 2006; Bekki & Forbes 2006), and the mass-metallicity relation for the blue GCs (Bekki et al. 2007), there are few simulation results that can be

| Galaxy | $M_r$ | $v_{sys}$ | $R_{gal}$ | $P_{A_{num}}$ | Distance |
|--------|------|---------|----------|-------------|----------|
| M60    |      |         |          |             |          |
| M87    |      |         |          |             |          |
| M49    |      |         |          |             |          |
| NGC 1399 | |      |          |             |          |
| NGC 5128 | |      |          |             |          |
| NGC 4636 | |      |          |             |          |

* Absolute $V$-magnitude based on $B_V$, $(B - V)_0$ (de Vaucouleurs et al. 1991), $A_V$ (Schlegel et al. 1998), and distance adopted in this study.

**Galaxy Samples**

| Galaxy | $M_r$ | $v_{sys}$ | $R_{gal}$ | $P_{A_{num}}$ | Distance |
|--------|------|---------|----------|-------------|----------|
| M60    |      |         |          |             |          |
| M87    |      |         |          |             |          |
| M49    |      |         |          |             |          |
| NGC 1399 | |      |          |             |          |
| NGC 5128 | |      |          |             |          |
| NGC 4636 | |      |          |             |          |

**Global Kinematic Properties of GCs in gEs**

| Galaxy | $\tau_\phi$ | $\sigma_\phi$ | $\theta_\phi$ | $\Omega$ | $\sigma_\phi R$ | $\Omega R/\sigma_\phi R$ |
|--------|-------------|---------------|---------------|---------|----------------|---------------------|
| M60    |             |               |               |         |                |                     |
| M49    |             |               |               |         |                |                     |
| NGC 1399 | |             |               |         |                |                     |
| NGC 5128 | |             |               |         |                |                     |
| NGC 4636 | |             |               |         |                |                     |
compared directly with the observational results summarized in Table 5 (Bekki et al. 2005; Kravtsov & Gnedin 2005).

In a pioneering work, Bekki et al. (2005) numerically investigated the kinematics of the GC system in E/S0 galaxies formed from a dissipationless merging of spiral galaxies. They presented kinematic properties such as rotation and velocity dispersion of the pre-existing MPCs and MRCs for several merger configurations (e.g., pair and multiple mergers). In regard to rotation, both MPCs and MRCs show larger rotation amplitudes in the outer region ($R > 2R_e$) than in the inner region ($R \sim R_e$), regardless of the merger configuration. Interestingly, observational data in Figure 16 show that the rotation amplitudes for the blue GCs do not change as the galactocentric distance increases. However, those for the red GCs increase marginally from the inner region to the outer region if we neglect NGC 4636 (filled pentagon), as predicted by the simulation. For the velocity dispersion, the MPCs show a slightly larger central velocity dispersion than the MRCs, indicating that the MPCs are dynamically hotter than the MRCs. Moreover, the VDPs for both MPCs and MRCs decrease as the galactocentric distance increases in all major merger models, while

![Fig. 15](#)

![Fig. 16](#)

**Fig. 15.**—Rotation-corrected velocity dispersions in gEs vs. the projected galactocentric distances for all GCs (top), the blue GCs (middle), and the red GCs (bottom). The rotation-corrected velocity dispersion is normalized with respect to that of all GCs in each gE. The projected galactocentric distance is normalized with respect to the effective radius of each gE. Open symbols indicate the dispersions in the inner region of each gE, while filled symbols indicate those in the outer region. [See the electronic edition of the Journal for a color version of this figure.]

**Fig. 16.**—Absolute values of the ratio of rotation amplitude to velocity dispersion vs. the projected galactocentric distances for all GCs (top), blue GCs (middle), and red GCs (bottom). Open symbols indicate the ratios in the inner region of each gE, while filled symbols indicate those in the outer region. [See the electronic edition of the Journal for a color version of this figure.]
they are sometimes very flat in multiple merger models. The kinematic data in Figure 15 show that the VDPs might be different depending on the galaxy (e.g., flat for M49 and increasing for M87), and a difference between VDPs in blue and red GCs appears to exist. Although the latter is not expected from the simulation, the former is consistent with the simulation, implying different merger histories depending on the galaxies.

Krivtsov & Gnedin (2005) studied the formation of GCs in a Milky Way–ized galaxy using a gas dynamics cosmological simulation with an adaptive refinement tree code. However, they had to stop the simulation at $z \approx 3.3$ due to limited computational resources. Later, Gnedin & Prieto (2006), using the separate collisionless $N$-body simulation described in Kravtsov et al. (2004) up to $z = 0$, calculated the GC orbits for a similar galactic system. They found that, at present, the GC orbits are isotropic in the inner 50 kpc region of the galactic center, but radial in the outer region. Although it is difficult to examine the observational data at large distances (>50 kpc) because of insufficient GC samples in that region, the isotropic orbit in the inner region is roughly consistent with the kinematic data of gEs (see Table 5).

On the other hand, Vesperini et al. (2003) modeled a dynamical evolution of the M87 GC system with different initial conditions for the mass function, the spatial distribution, and the velocity anisotropy of the GC system, following the evolution of a model GC system given by Vesperini (2000, 2001). In their result, for a two-slope power-law initial mass function of the GCs corresponding to the mass function of the old clusters, a flat radial profile for the mean mass of the GCs obtained from the observation can be acquired from the simulation with any velocity anisotropy of the GC system. However, for a power-law initial mass function of the GCs corresponding to that of the young clusters, the observed flat radial profile for the mean mass of the GCs can be obtained from the simulation only with a strong radial anisotropy of the GC system. This initial radial anisotropy is much more radially biased than the one observed in the GC systems of gEs (which have mostly isotropic velocity ellipsoids, as seen in Table 5), which raises a problem in that a young GC system in mergers like the Antennae may evolve into the GC system seen in gEs.

By viewing the formation of the M60 GC system in the context of the kinematic predictions of the above models, the strong rotations of the blue and red GC systems are consistent with the simulation of Bekki et al. (2005). However, the larger velocity dispersion of the red GCs compared to the blue GCs in M60 is not consistent with the predictions of several formation models. M60 might be a special case among gEs due to a possible interaction with its companion galaxy, NGC 4647. Although they have been regarded as a noninteracting system (e.g., Sandage & Bedke 1994), recent observational results suggest evidence of current interaction between the two: (1) the morphological structure of NGC 4647 is clearly asymmetric (Koopman et al. 2001); (2) the stellar kinematic study shows that the inner region of M60 has strong rotational support compared to other gEs, and has an asymmetric rotation curve (Pinkney et al. 2003; de Bruyne et al. 2001); (3) an X-ray filament that extends to the northeastern edge of M60 can be seen (Randall et al. 2006); and (4) young luminous star clusters or associations in NGC 4647 have been found (Lee et al. 2007). However, Pierce et al. (2006) found no obvious signs of a recent starburst, interaction, or merger by estimating the ages and metallicities from the spectra of M60 GCs. Thus, it appears that the interaction between the two started very recently, and did not affect the old M60 GC system significantly. The spatial coverage of observed GCs in Pierce et al. (2006) is not enough to study the interacting region between M60 and NGC 4647 (see Fig. 1). Therefore, to understand the formation of the M60 GC system in terms of an interaction between galaxies, it is important to obtain a large spectroscopic sample of GCs at larger galactocentric distances with a signal-to-noise ratio high enough to determine the age and metallicity.

5. SUMMARY

Using the photometric and spectroscopic database of 121 GCs (83 blue GCs and 38 red GCs) in the gE M60 (NGC 4649) in the Virgo cluster, we have investigated the kinematics of the GC system of this galaxy. Our primary results are summarized below.

1. In a case similar to that of the M87 GCs (Côte et al. 2001), the combined, blue, and red GC subsamples of M60 show significant overall rotations. The rotation axes are nearly perpendicular to the line connecting M60 and its companion NGC 4647.

2. Both the velocity dispersion about the mean velocity and about the best-fit rotation curve of the red GCs are marginally larger than those of the blue GCs. This implies that the red GC system might be dynamically hotter than the blue GC system, unlike the GC systems in other gEs.

3. Comparison of observed stellar and GC velocity dispersion profiles with those calculated from the stellar mass profile showed that the mass-to-light ratio is not constant, but should increase as the galactocentric distance increases, indicating the existence of an extended dark matter halo in M60.

4. Using the X-ray mass profile, the number density distribution of GCs, and the observed VDP of GCs, we have determined the velocity ellipsoids of the M60 GC system. The system of all the GCs in M60 appears to have a tangentially biased velocity ellipsoid, unlike the GC systems in other gEs. Two subsamples have a different velocity anisotropy: the blue GCs show a modestly tangentially biased velocity ellipsoid, while the red GCs show a modestly radially biased or an isotropic velocity ellipsoid.

5. We have compared the kinematics of the M60 GC system in this study with the results of other GC systems in gEs. On the whole, the rotation-corrected velocity dispersion of blue GCs is similar to or larger than that of the GCs, which is not the case for the M60 GC system. The rotation of the GC system in gEs is not negligible, which is in contrast to the traditional view, although the details of rotation amplitudes and rotation axes need to be investigated further. The sample of all GCs in each GC system appears to have an isotropic velocity ellipsoid, while the red GC and blue GC subsamples do not show unified velocity anisotropy.

In conclusion, the GC systems in gEs have common kinematic properties such as velocity dispersion, while the properties of rotation and velocity anisotropy show diverse results. These kinematic properties are not fully explained by any current models. We need extensive kinematic studies of other GC systems over larger galactocentric distances with various environmental effects to understand the diversity of the kinematics, and the formation and evolution of GC systems in gEs. Moreover, it is desirable to have more elaborate model predictions for the kinematics of GC systems in gEs, including the velocity anisotropy.

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