Mysterious Globular Cluster System of the Peculiar Massive Galaxy M85

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Abstract

We present a study on the stellar population and kinematics of globular clusters (GCs) in the peculiar galaxy M85. We obtain optical spectra of 89 GCs at 8 kpc < R < 160 kpc using the MMT/Hectospec. We divide them into three groups, blue/green/red GCs (B/G/RGCs), with their (g − i)$_{0}$ colors. All GC subpopulations have mean ages of about 10 Gyr, but showing differences in metallicities. The BGCs and RGCs are the most metal-poor ([Z/H] ~ −1.49) and metal-rich ([Z/H] ~ −0.45), respectively, and the GGCs are in between. We find that the inner GC system exhibits a strong overall rotation that is entirely due to a disklike rotation of the RGC system. The BGC system shows little rotation. The GGCs show kinematic properties clearly distinct among the GC subpopulations, having higher mean velocities than the BGCs and RGCs and being aligned along the major axis of M85. This implies that the GGCs have an origin different from the other GC subpopulations. The rotation-corrected velocity dispersion of the RGC system is much lower than that of the BGC system, indicating the truncation of the red halo of M85. The BGCs have a flat velocity dispersion profile out to R = 67 kpc, reflecting the dark matter extent of M85. Using the velocity dispersion of the BGC system, we estimate the dynamical mass of M85 to be 3.8 × 10$^{12}$ $M$_{⊙}. We infer that M85 has undergone merging events lately, resulting in the peculiar kinematics of the GC system.

Unified Astronomy Thesaurus concepts: Lenticular galaxies (915); Elliptical galaxies (456); Virgo Cluster (1772); Globular star clusters (656)

Supporting material: machine-readable tables

1. Introduction

Massive elliptical galaxies have formed via continuous mergers in the hierarchical galaxy formation model (Toomre & Toomre 1972). In this scenario, merger remnant galaxies show a snapshot of evolutionary stages between disk and elliptical galaxies. Many studies reported that nearby elliptical galaxies have fine structures produced during past mergers (e.g., Schweizer 1982; Duc et al. 2015).

One of the nearby merger remnant galaxies that show interesting merging features is M85 (NGC 4382, VCC 798). Because of these merger remnant features, the morphological type of M85 has been uncertain. Binggeli et al. (1985) and de Vaucouleurs et al. (1991) classified M85 as an S0pec because of its diskylike structures in addition to its prominent bulge. However, Kormendy et al. (2009) suggested that its morphological type is E2, not S0, because the a$_{4}$ profile derived from ellipse fitting does not indicate any disky structure at the radial range of 26″ < R < 221″, corresponding to 2 kpc < R < 19 kpc at a distance to M85 of 17.9 Mpc (Blakeslee et al. 2009), where the light excess in the surface brightness profile appears.

In general, elliptical galaxies are divided into two groups, called an “E-E dichotomy” (Kormendy et al. 2009, and references therein): (1) giant ellipticals (M$_{V}$ < −21.5 mag), which generally have cuspy cores and boxy distorted isophotes, rarely rotate, and have mostly old stars, and (2) normal and dwarf ellipticals (M$_{V}$ > −21.5 mag) that lack cores but have extra light at the center, strongly rotate with disky distorted isophotes, and have younger stars. Interestingly, M85 is an exceptional case in this dichotomy. It is classified as a giant elliptical galaxy according to its brightness, M$_{V}$ = −22.52 mag (Kormendy et al. 2009). It has a core and boxy isophotes within 1″ from the galaxy center (Ferrarese et al. 2006). These are all general properties of giant ellipticals. However, M85 also shows unusual properties that giant ellipticals rarely have. Several studies found that the nucleus of M85 is as young as a few Gyr based on the spectroscopic analysis (Fisher et al. 1996; Terlevich & Forbes 2002; Ko et al. 2018). In addition, Emsellem et al. (2007) classified M85 as a fast rotator with a projected specific angular momentum of J$_{p}$ = 0.155 at one effective radius (R$_{e}$ = 67″). These properties are related to postmerger events.

All of these studies about the stellar light of M85 focused on the central region within one effective radius. There have been several studies that investigated a wider region of M85 using globular clusters (GCs) that are a useful tool to study galaxy halo structures (Peng et al. 2006; Chies-Santos et al. 2011; Trancho et al. 2014). These studies found that the GCs in M85 also show peculiar properties, like the central stars in M85. In general, GCs in massive early-type galaxies show a bimodal optical color distribution, which indicates the existence of two GC subpopulations: old metal-poor (blue) and old metal-rich (red) GCs. However, the GCs at R < 2″ (10 kpc) in M85 do not clearly show a bimodal color distribution (Peng et al. 2006). This implies the presence of intermediate-age GCs, indicating that their host galaxies have experienced mergers accompanying intense star formation a few Gyr ago. Chies-Santos et al. (2011) and Trancho et al. (2014) confirmed the existence of the intermediate-age GC populations in M85 using the
combination of optical and $K$-band photometry. These previous studies covered only the central region at $R < 2'$. In this context, we performed a wide-field photometric survey of the GCs in M85, covering a $1^\circ \times 1^\circ$ field (Ko et al. 2019, hereafter Paper I). We identified 1318 GC candidates in the survey region and found that the radial extent of the GC system of M85 is as large as $R = 20' \ (104 \ kpc)$. Also, we detected a number of intermediate-color GC candidates in the central region ($R < 2'$), which is consistent with the previous study (Peng et al. 2006). As a follow-up, Ko et al. (2018, hereafter Paper II) measured the ages and metallicities of 20 GCs in M85 using the optical spectra obtained with the Gemini/GMOS. We found that 55% of the GCs have mean ages of about 4 Gyr, much younger than typical GCs. In addition, we detected a strong disklke rotation of the GC system with a rotation amplitude of 148 km s$^{-1}$. However, these results need to be supplemented with a larger sample because this spectroscopic survey covers only the small central region at $R < 3' \ (16 \ kpc)$, although the M85 GC system is extended to $R = 20'$ according to the photometric survey (Paper I).

In this study, we present a wide-field spectroscopic survey of the GCs in M85 to investigate the physical properties of the GCs in the outskirts of M85. We cover $R < 30' \ (156 \ kpc)$ using the Hectospec (Fabricant et al. 2005) on the 6.5 m MMT. To date, this GC survey covers the widest area around M85. This paper is organized as follows. We briefly describe the spectroscopic target selection, observation, and data reduction in Section 2. In Section 3, we identify genuine GCs and investigate the stellar population and kinematic properties of GC subpopulations of M85. We discuss the peculiarity of the M85 GC system and investigate the dark matter extent of M85, as well as dynamical mass estimation, in Section 4. We summarize the results in Section 5.

2. Observation and Data Reduction

2.1. Target Selection and Spectroscopic Observation

We selected the spectroscopic targets from the photometric sample of GC candidates around M85 in Paper I. The GC candidates were identified as pointlike sources in the $ugi$-band images taken with the MegaCam at the 3.8 m Canada–France–Hawaii Telescope. We used the $(u - g)_0$ and $(g - i)_0$ color combination to select the GC candidates. The magnitude range for the target selection was set to be $18 < i_0 < 22$ in order to minimize the contamination of foreground stars. The spatial distribution of these GC candidates is shown in Figure 1(a). We assigned fibers to a total of 645 GC candidates for spectroscopic observations (Figure 1(b)). In addition to the GC candidates, we obtained spectra of the M85 nucleus and a hypercompact star cluster, M85-HCC1, discovered by Sandoval et al. (2015).

We carried out spectroscopic observations using the Hectospec mounted on the 6.5 m MMT (Program ID: 2016A-UAO-G4, PI: Youkyung Ko) during 2016 March. We selected a 270 mm$^{-1}$ grating with a dispersion of 1.2 Å pixel$^{-1}$,
covering the wavelength range of 3650–9200 Å. Three different configurations with a slight offset, covering the \( R < 30' \) region around M85, were made, as shown in Figure 1(b). We used the exposure time of 7200 s (five times 1440 s) for each of the two configurations (M85-B1 and B2) to cover bright targets, and we used the longer exposure time of 9000 s (five times 1800 s) for one configuration (M85-F1) to cover fainter targets. The seeing ranged from 0.79 to 1.2' during the observations. The field coordinates and exposure times are given in Table 1.

We calculated the completeness of the mask design, defined as the ratio between the targets on which fibers are allocated and photometric samples \((N(\text{target})/N(\text{phot}))\), as functions of galactocentric distance, position angle, and \( i \)-band magnitude (Figures 1(c)–(e)). We found that the completeness is almost constant (\( \sim 30\% \)) over entire radial and azimuthal ranges, indicating that there is no bias on the target allocation along the location. The completeness is constant for the bright sources with \( i_0 < 21 \) mag but decreases for the fainter sources.

In addition, we compared the color distribution of the photometric samples with that of the targets on which fibers are assigned. The fiber allocation rate is constant (\( \sim 30\% \)) in the color range of 0.55 \(< (g - i) < 1.2 \) that corresponds to the GC color, indicating that there is no bias on the target selection.

### 2.2. Data Reduction and Radial Velocity Measurements

We used version 2.0 of the HSRED reduction pipeline\(^5\) for data reduction. It includes bias and dark correction, flat-fielding, aperture extraction of spectra, and wavelength calibration. Flux calibration was done following the methods described by Fabricant et al. (2008). Most of the faint targets with \( i > 21.0 \) mag have low signal-to-noise ratios \((\text{S/N} < 5)\). The median \( \text{S/N} \) of the spectra of GC candidates with \( i < 21.0 \) mag at 5000 Å is \( \text{S/N} \sim 10 \).

We estimated the heliocentric radial velocities of spectroscopic targets using the xcsao task in the IRAF RVSAO package (Kurtz & Mink 1998). The prominent absorption lines in the wavelength range of 3800–5400 Å were used to apply the cross-correlation method (Tonry & Davis 1979). The RVSAO package presents several radial velocity templates, such as spectra of an A star, M31 GCs, and elliptical and spiral galaxies. We used 10 templates and matched the targets with \( v_i > 3000 \) and \(< 3000 \) km s\(^{-1}\) with galaxy and GC templates, respectively. For 115 of the 645 targets, we could not derive reliable radial velocities because of low \( \text{S/N} \) \((\text{S/N} < 5)\). In addition, we excluded 21 targets fainter than the luminosity of the galaxy light within the fiber, using the surface brightness profile of M85 from Kormendy et al. (2009).

\(^5\) This is an updated reduction pipeline originally developed by Richard Cool; more details can be found at http://www.mnuto.org/node/536.

We also measured radial velocities of the M85 nucleus and M85-HCC1 and compared the measurements with the results in previous studies. The radial velocity of the M85 nucleus is derived to be \( v_i = 695 \pm 16 \) km s\(^{-1}\), which is smaller than those in several previous studies, \( v_i = 729–760 \) km s\(^{-1}\) (Smith et al. 2000; Gavazzi et al. 2004; Paper II). In the case of M85-HCC1, the radial velocity is measured to be \( v_i = 655 \pm 7 \) km s\(^{-1}\), which is consistent with the result from the Sloan Digital Sky Survey (SDSS) DR15 (Aguado et al. 2019), \( v_i = 664 \pm 5 \), within the uncertainties. We did not add any offset value to the radial velocities we measured because the velocity measurements for the point source M85-HCC1 agree well.

We calculated the spectroscopic success rate, defined as the number ratio between the targets of which radial velocities are well derived and the parent photometric sample \((N(\text{success})/N(\text{phot}))\) as a function of galactocentric distance from M85 (Figure 1(e)). We found that the success rates are almost constant at \( \sim 30\% \) for the whole radial range. For comparison, we also calculated the number fraction of the targets with velocity measurements to the spectroscopic targets on which fibers were allocated \((N(\text{success})/N(\text{target}))\). This fraction does not vary significantly with distance from M85. The azimuthal variations of \( N(\text{success})/N(\text{phot}) \) and \( N(\text{success})/N(\text{target}) \) are similar to their radial variations (Figure 1(d)). Therefore, we conclude that there is no bias in the velocity measurements along the target location. In addition, we checked \( N(\text{success})/N(\text{phot}) \) and \( N(\text{success})/N(\text{target}) \) as a function of \( i \)-band magnitude (Figure 1(e)). We found that the radial velocities of all bright targets with \( i_0 < 21 \) mag are successfully measured with a mean spectroscopic success rate of 40%.

Figure 2 shows radial velocity uncertainties versus dereddened \( i \)-band magnitudes for the spectroscopic targets classified into GCs, foreground stars, and background galaxies (see Section 3.1). On average, brighter sources have smaller velocity uncertainties than fainter sources. The mean radial velocity uncertainty of the sources with \( i_0 < 19.5 \) mag, which are mostly foreground stars, is 11 km s\(^{-1}\). Most of the GCs have \( i \)-band magnitudes of 19.5 mag < \( i_0 < 21 \) mag, where the mean velocity uncertainty ranges from 15 to 30 km s\(^{-1}\). The velocity uncertainties of background galaxies are mostly smaller than 20 km s\(^{-1}\), regardless of their luminosity. This is because the velocity measurements for the faint galaxies were based on emission lines that are much stronger and narrower than absorption lines.

### 3. Results

#### 3.1. GC Selection and Subpopulations

We classified the observed targets into GCs, foreground stars, and background galaxies. First, there are 110 background galaxies with \( v_i > 3000 \) km s\(^{-1}\). The radial velocity distribution

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**Table 1**

**Observation Log for the MMT/Hectospec Run**

| Mask Name | \( \alpha \) (J2000) | \( \delta \) (J2000) | \( N \)^\( \star \) | Exp. Time | Seeing | Date (UT) |
|-----------|----------------------|---------------------|------------------|-----------|---------|-----------|
| M85-B1    | 12:25:24.74          | +18:10:21.3         | 256              | 5 × 1440 s | 1.2'3   | 2016 Mar 7 |
| M85-B2    | 12:25:20.08          | +18:05:08.9         | 260              | 5 × 1440 s | 0.9'9   | 2016 Mar 16 |
| M85-F1    | 12:25:26.52          | +18:07:07.6         | 250              | 5 × 1800 s | 1.2'2   | 2016 Mar 17 |

\(^\star\) Number of object fibers among 300 fibers in each field. The remaining fibers are assigned to sky regions.
of the galaxies in the Virgo Cluster field shows a clear separation at $v_r = 3000 \text{ km s}^{-1}$ (Kim et al. 2014). We adopted this criterion to divide the targets into the objects bound to the Virgo Cluster and background galaxies. The radial velocities of the background galaxies in this sample range from 16,883 to 151,120 km s$^{-1}$, which is much higher than the mean velocity of the Virgo Cluster galaxies in the survey region, $v_r \sim 1056 \text{ km s}^{-1}$ (Kim et al. 2014).

The targets with $v_r < 3000 \text{ km s}^{-1}$ are either M85 GCs or foreground stars. The radial velocity distribution of these targets clearly shows two peaks at $v_r \sim 0$ and 700 km s$^{-1}$ (Figure 3(a)) corresponding to foreground stars and M85 GCs, respectively. To decompose these two populations, we performed a Gaussian mixture modeling (GMM; Muratov & Gnedin 2010), assuming bimodal distribution with different variances. The $p$ and $D$ values derived from the GMM indicate the probability of the unimodal distribution and the peak separation relative to the Gaussian width, respectively. In this case, the $p$-value is smaller than 0.0001, and the $D$ value is 5.01, which means that the input radial velocity distribution is not unimodal and has a clear peak separation.

The mean radial velocities of the two populations are $v_r = 22 \pm 6$ and $754 \pm 23 \text{ km s}^{-1}$, and the Gaussian widths are $111 \pm 4$ and $174 \pm 15 \text{ km s}^{-1}$, respectively. According to the GMM results, we adopted the point where two Gaussians cross ($v_r = 350 \text{ km s}^{-1}$) as the radial velocity criterion for dividing the targets into GCs and foreground stars. We consider 89 targets with $v_r > 350 \text{ km s}^{-1}$ and 310 targets with $v_r < 350 \text{ km s}^{-1}$ to be GCs and foreground stars, respectively. Tables 2 and 3 list the photometric properties and radial velocities of the GCs and contaminants (foreground stars and background galaxies), respectively.

Figure 3(b) shows the $(g - i_0)$ colors and radial velocities of GCs and foreground stars confirmed in this study. The magnitudes are based on the CFHT/MegaCam AB system. We used a foreground extinction value of $E(B - V) = 0.024 \text{ mag}$ ($E(g - i) = 0.049 \text{ mag}$) for M85 (Schlafly & Finkbeiner 2011). The foreground stars show a clear sequence at $v_r = 0 \text{ km s}^{-1}$ with a broad color range of $(g - i_0) = 0.5$–1.15, while the GCs have a narrower color range of $(g - i_0) = 0.55$–1.0 at $v_r = 750 \text{ km s}^{-1}$. Figure 3(c) displays that the $(g - i_0)$ color distribution of the GCs shows a dominant peak at $(g - i_0) = 0.675$ and a much weaker peak at $(g - i_0) = 0.925$, which is consistent with those of the parent sample (Paper I). The foreground stars have a strong blue peak at $(g - i_0) = 0.575$ and a red tail in the $(g - i_0)$ color distribution.

We calculated rolling averages of velocities as a function of $(g - i_0)$ color with moving bins of $N = 12$ and noted that intermediate-color GCs with $0.7 \lesssim (g - i_0) \lesssim 0.8$ have radial velocities higher than the other GCs (Figure 3(b)). It has been known that the GCs in M85 show a tricominal color distribution, while the GCs in massive early-type galaxies often show a bimodal color distribution (Peng et al. 2006). Paper I also suggested that M85 has an intermediate-color GC population with a mean color of $(g - i_0) \sim 0.78$ based on the GMM tests despite a high uncertainty of its number fraction. Because we identified a velocity peculiarity of these green GCs (GGCs) with $0.7 < (g - i_0) < 0.8$, we consider them as a separate population, in addition to blue GCs (BGCs) with $(g - i_0) < 0.7$ and red GCs (RGCs) with $(g - i_0) > 0.8$. The number of BGCs, GGCs, and RGCs in M85 is 41, 32, and 16, respectively. The subpopulations information of the GCs is also listed in Table 2.

Figure 3 shows the spatial distributions of the GC subpopulations within a $25' \times 15'$ field, focusing on three galaxies: M85, NGC 4394 (east), and IC 3292 (west). Panel (a)
Table 2  Spectroscopic and Photometric Properties of the GCs Confirmed in This Study

| ID  | $\alpha$ (12000) (deg) | $\delta$ (12000) (deg) | $g$ (mag)  | $(g-i)^0$ (mag) | $C^0$ (mag) | $v_\text{ls}$ (km s$^{-1}$) | Class |
|-----|------------------------|------------------------|------------|-----------------|-------------|--------------------------|-------|
| GC01| 185.892609             | 18.149979              | 19.429 ± 0.002 | 0.822 ± 0.003  | 0.02        | 395 ± 14                  | GGC   |
| GC02| 185.961578             | 18.098152              | 21.175 ± 0.005 | 0.792 ± 0.009  | 0.12        | 884 ± 74                  | GGC   |
| GC03| 185.973221             | 17.820648              | 20.941 ± 0.005 | 0.840 ± 0.008  | 0.14        | 960 ± 69                  | GGC   |
| GC04| 186.040955             | 18.078588              | 20.691 ± 0.004 | 0.754 ± 0.006  | 0.08        | 734 ± 55                  | GGC   |
| GC05| 186.095642             | 18.139322              | 20.314 ± 0.003 | 0.734 ± 0.005  | 0.07        | 997 ± 39                  | BGC   |

Notes. Table 2 is published in its entirety in the electronic edition. The five sample GCs are shown here as guidance for the table’s form and content.

a) CFHT/MegaCam AB magnitudes.

b) The inverse concentration index $C$ defined as the $i$-band magnitude differences between 4 and 8 pixel diameter aperture photometry.

c) Classifications are BGC (blue GC with $(g-i)_0 < 0.7$), GGC (green GC with $0.7 < (g-i)_0 < 0.8$), and RGC (red GC with $(g-i)_0 > 0.8$).

(This table is available in its entirety in machine-readable form.)

displays the $g$-band image taken with the CFHT/MegaCam (Paper I) showing fine structures of M85, such as shells and ripples, reaching galaxies on either side. In particular, prominent shells are extended along the NE–SW direction. In addition, we detect a warped faint stellar halo of IC 3292. The spatial distribution of the BGCs is more extended than that of the RGCs. Interestingly, the GGCs are lined up in the direction of NE–SW. We will investigate and discuss the spatial and kinematic peculiarities of the GC subpopulations in the following sections.

Figure 5 shows $(g-i)_0$ color–magnitude diagrams for pointlike sources (gray dots) detected in the CFHT/MegaCam images (Paper I), as well as the GCs (red filled circles) and foreground stars (blue open triangles) confirmed in this study. We divided the objects into two groups according to their inverse concentration indices. The inverse concentration index $C$ is defined as the difference between 4 and 8 pixel diameter $i$-band aperture-corrected magnitudes. This parameter is broadly used to distinguish slightly extended sources from pointlike sources (e.g., Durrell et al. 2014; Paper I). We found that 81% of the confirmed GCs have $C$ values higher than 0.05, while 98% of the confirmed foreground stars have lower $C$ values. This indicates that most GCs in M85 are slightly extended in the CFHT/MegaCam images.

3.2. Stellar Population of GC Subpopulations

We estimated the mean ages and metallicities of the GC subpopulations using their coadded spectra to compare their formation epochs. Figure 6 shows the coadded spectra of three GC subpopulations (BGCs, GGCs, and RGCs), as well as the spectrum of the M85 nucleus. The coadded spectra have higher $S/N$s ranging from 28 to 45 compared to the individual target spectra. Several prominent absorption lines are marked in panels (d) and identified in the other spectra as well. The spectrum of the M85 nucleus shows broader absorption lines than those of the GCs because of the larger velocity dispersion of the M85 nucleus.

We measured the Lick indices using the EZ_Ages package (Graves & Schiavon 2008). The Lick indices have been widely used to measure ages and metallicities of old simple stellar populations (Burstein et al. 1984; Worthey et al. 1994; Worthey & Ottaviani 1997; Trager et al. 1998). The stacked spectra were smoothed with Lick resolution ($\sim$9 Å). We adopted a $\chi^2$ minimization technique using the residual between the observed Lick indices and the model prediction values to determine the ages and metallicities of the GCs (Proctor et al. 2004). We used flux-calibrated stellar population models of Lick indices from Thomas et al. (2011), for which the ages range from 0.1 to 15 Gyr, the metallicities $[Z/H]$ range from $-2.25$ to $+0.67$, and the $\alpha$-element abundances $[\alpha/Fe]$ range from $-0.3$ to $+0.5$. In the beginning, we used all Lick indices except CN1, CN2, Ca4227, and NaD indices for the fitting. The CN1, CN2, and Ca4227 indices are too sensitive to nitrogen abundances that are not well calibrated in the models we adopted, and the NaD index strongly depends on the amount of interstellar absorption. Afterward, we calculated the $\chi^2$ values with the rest of the Lick indices using iterative $2\sigma$ clipping. The detailed process is described in Paper II.

We estimated the uncertainties of the mean ages, $[Z/H]$, and $[\alpha/Fe]$ using a bootstrapping method. For each subpopulation, we randomly chose the same number of GCs from the actual parent data allowing replacement, stacked their spectra, and measured ages and metallicities with the spectra. After repeating this procedure 1000 times, we identified 16th and 84th percentiles from the results. The differences between these values and the results derived from the actual data were adopted as the uncertainties.

Table 4 lists the mean ages, $[Z/H]$, and $[\alpha/Fe]$ values of the GC subpopulations and the nucleus of M85. The mean ages of BGCs, GGCs, and RGCs are 14.0$^{+0.1}_{-0.5}$, 11.1$^{+3.4}_{-3.2}$, and 9.9$^{+2.1}_{-3.7}$ Gyr, respectively, which are consistent within the uncertainties.

On the other hand, the GC subpopulations show differences in their metallicities. The BGCs and RGCs have mean metallicities of $[Z/H] = -1.49^{+0.20}_{-0.04}$ and $-0.45^{+0.22}_{-0.11}$, respectively, showing that they are the most metal-poor and metal-rich populations. They are consistent with those in other galaxies with the same luminosity as M85 ($M_B = -21.28$ mag; Binggeli et al. 1985), according to the GC mean metallicity and host galaxy luminosity (Peng et al. 2006). The GGCs in M85 have a mean metallicity of $[Z/H] = -0.91^{+0.20}_{-0.12}$, which is between those of the BGCs and RGCs. The $\alpha$-element abundances of the GC subpopulations range from 0.15 to 0.24, but it is hard to tell any significant difference because of large uncertainties.

We derived the age, metallicity, and $[\alpha/Fe]$ values of the M85 nucleus to be about 2.9 Gyr, $[Z/H] = +0.26$, and $[\alpha/Fe] = +0.24$. These values are similar to those derived using the Gemini/GMOS optical spectrum in Paper II. This shows that the stellar population in the M85 nucleus is much younger and more metal-rich than any GC subpopulation identified in this study. We could not find any GC populations that were formed when the central star formation occurred in the nucleus.
Table 3

| ID   | α (J2000) (deg) | δ (J2000) (deg) | i (mag) | (g − i) (mag) | C (mag) | v_r (km s^{-1}) |
|------|----------------|----------------|---------|---------------|---------|-----------------|
| Star01 | 185.835114 | 18.226645 | 20.423 ± 0.004 | 0.689 ± 0.006 | -0.02 | -146 ± 40 |
| Star02 | 185.835785 | 18.116449 | 20.406 ± 0.004 | 0.849 ± 0.006 | -0.02 | 0 ± 22 |
| Star03 | 185.839340 | 18.155159 | 20.080 ± 0.002 | 1.005 ± 0.004 | 0.00 | 105 ± 20 |
| Star04 | 185.846497 | 18.014795 | 20.407 ± 0.003 | 0.629 ± 0.005 | 0.00 | 340 ± 37 |
| Star05 | 185.849579 | 18.077505 | 20.706 ± 0.004 | 0.789 ± 0.006 | 0.02 | 169 ± 64 |

Galx001 | 185.882706 | 18.143103 | 21.300 ± 0.006 | 0.554 ± 0.009 | 0.32 | 46086 ± 6 |
Galx002 | 185.896484 | 17.997314 | 21.896 ± 0.011 | 0.618 ± 0.015 | 0.25 | 31115 ± 10 |
Galx003 | 185.901016 | 17.980145 | 21.834 ± 0.010 | 0.489 ± 0.013 | 0.31 | 46201 ± 11 |
Galx004 | 185.904617 | 18.043806 | 19.892 ± 0.002 | 0.955 ± 0.004 | 0.38 | 34970 ± 9 |
Galx005 | 185.906403 | 18.105858 | 21.971 ± 0.011 | 0.832 ± 0.017 | 0.22 | 46142 ± 11 |

Notes. Table 3 is published in its entirety in the electronic edition. The five sample stars and galaxies are shown here as guidance for the table’s form and content.

a CFHT/MegaCam AB magnitudes.

b The inverse concentration index C defined as the difference between 4 and 8 pixel diameter i-band aperture-corrected magnitudes.

(This table is available in its entirety in machine-readable form.)

3.3. Kinematics of the GC System in M85

We investigate the kinematic properties of the GC system of M85, such as mean radial velocities, rotation properties, and velocity dispersions. We used a numerical bootstrapping method to estimate the uncertainties of all kinematic parameters. We randomly chose the same number of GCs from the parent data, allowing replacement to construct a mock data set, and derived their kinematic parameters. After repeating this procedure 1000 times, we identified 16th and 84th percentiles for the results, which corresponds to 68% confidence intervals. We adopted the differences between these values and the parameters measured from the actual parent data as uncertainties.

We compare the mean radial velocities, rotation properties, and velocity dispersions of the GC subpopulations in the following sections. Table 5 lists the kinematic parameters derived for the entire GC, BGC, GGC, and RGC systems.

3.3.1. Mean Radial Velocities

Figure 7 shows radial velocity distributions of all GCs and GC subpopulations confirmed in this study as a function of galactocentric distance from M85. All GCs are located in the radial range of 1.5 < R < 31.0 that corresponds to 8 kpc < R < 162 kpc. The BGCs and GGCs are found in the entire radial range, but all RGCs are within R = 6′ except for one.

The mean radial velocity of all GCs is \( \overline{v_r} = 754 ± 19 \) km s\(^{-1}\), which is 58 km s\(^{-1}\) higher than the radial velocity of the M85 nucleus, 696 ± 16 km s\(^{-1}\). About two-thirds of the GCs have radial velocities higher than the nucleus velocity (Figure 7(b)). This number excess of the high-velocity GCs is mainly contributed by the GGCs that have a much higher mean radial velocity of \( \overline{v_r} = 812^{+36}_{-30} \) km s\(^{-1}\). If the GGCs are excluded, the mean radial velocity of the GCs drops to \( \overline{v_r} = 721^{+23}_{-21} \) km s\(^{-1}\). In addition, the BGCs and RGCs have...
similar mean radial velocities of $\overline{V} = 727^{+30}_{-23}$ and $704 \pm 37$ km s$^{-1}$, respectively. These mean radial velocities measured without the GGC population are consistent with the radial velocity of the M85 nucleus within the uncertainties.

We performed two-sided Kolmogorov–Smirnov (K-S) tests to compare the radial velocity distributions of GC subpopulations. Figure 8 shows the cumulative radial velocity distributions of BGCs, GGCs, and RGCs in M85. The $p$-value for the BGCs and RGCs is 0.46, from which we cannot tell a clear difference between their velocity distributions. However, the $p$-values for the B/RGCs and GGCs are 0.07, meaning that the GGCs have a radial velocity distribution clearly distinct from those of both BGCs and RGCs.

In Figure 7, we also plot the radial velocities of dwarf galaxies in the Virgo Cluster for comparison with the M85 GC kinematics. We adopted the radial velocities of Virgo galaxies from the Extended Virgo Cluster Catalog (EVCC; Kim et al. 2014). There are only four dwarf galaxies in our survey region: VCC 797 (EVCC 556) at $R = 3 \pm 1$, VCC 751 (EVCC 529) at $R = 8.5$, EVCC 671 at $R = 18.7$, and EVCC 629 at $R = 24.6$. Two of them have radial velocities similar to the M85 velocity ($v = 696$ km s$^{-1}$ for VCC 751 and 703 km s$^{-1}$ for EVCC 617), but the other two have much higher velocities ($v = 1228$ km s$^{-1}$ for VCC 797 and 1408 km s$^{-1}$ for EVCC 629). Because of the small number statistics, it is not clear whether these dwarf galaxies constitute a distinguishable group associated with M85 or are governed by the gravitational potential of the Virgo Cluster. We will discuss the kinematic differences between M85 GCs and Virgo dwarf galaxies with regard to the dark matter extent of M85 in Section 4.2.

### Rotation Properties

Figure 9(a) shows the spatial distribution of the GCs along with their radial velocities. The GCs are strongly concentrated around the galaxy center and show an elongated spatial distribution. For comparison, we plot the isophotes of the M85 stellar light in Figure 9(b). The position angles and ellipticities of the isophotes change from $16^\circ$ to $66^\circ$ and from 0.18 to 0.38 as the semimajor axis $R_{maj}$ increases from 3$^\prime$ to 10$^\prime$ (Kormendy et al. 2009). The GCs show a spatial distribution elongated along the major axis of the isophote of M85 at $R_{maj} = 10^\prime$.

We also investigate the spatial distributions of the GC subpopulations separately (Figures 9(c)–(e)). The BGCs are sparsely distributed without any trend in their radial velocities. In contrast, the RGCs are strongly concentrated around the galaxy center and show a clear spatial segregation between high and low radial velocity GCs. We consider that this spatial segregation of the RGCs indicates a rotation signature of the
the same as Radial velocity distribution of all GCs. Panels 6.6 1.9 18 samples are similar to those of the photometric samples with These features in the spatial distributions of the spectroscopic M85, especially for the ones with higher relative velocities. RGC system. Interestingly, the GGCs are strongly aligned targets into GCs and foreground stars indicate the radial velocity of the M85 nucleus and the criteria used to divide the GGC system. (Kim et al. 2014) but for BGCs, GGCs, and RGCs, respectively. RGCs: 16 GCs with 0.8 < (g − i)0 < 1.0

![Figure 7](image_url)

**Figure 7.** (a) Radial velocity vs. galactocentric distance from M85 for all GCs. The filled circles and crosses represent the GCs and Virgo dwarf galaxies in the survey region (Kim et al. 2014), respectively. The dashed and dotted lines indicate the radial velocity of the M85 nucleus and the criteria used to divide the targets into GCs and foreground stars (v_r = 350 km s^{-1}), respectively. (b) Radial velocity distribution of all GCs. Panels (c)-(d), (e)-(f), and (g)-(h) are the same as (a)-(b) but for BGCs, GGCs, and RGCs, respectively.

RGC system. Interestingly, the GGCs are strongly aligned along the photometric major axis of the outer stellar isophote of M85, especially for the ones with higher relative velocities. These features in the spatial distributions of the spectroscopic samples are similar to those of the photometric samples with 18 < i_0 < 22 identified by Paper I (Figures 9(f)-(h)).

![Figure 8](image_url)

**Figure 8.** Cumulative radial velocity distributions of BGCs (dashed line), GGCs (solid line), and RGCs (dotted line).

For a quantitative comparison between spatial distributions of the GC subgroups, we performed two-sided K-S tests on their major and minor axes distances, adopting the major and minor axes of the isophote of M85 at R_{min} = 10'. Figure 10 shows the cumulative major and minor axis distances of the GC subpopulations. The distributions of the BGCs and GGCs are more extended along the major axis than the RGCs. The RGCs have a major axis distance distribution clearly distinct from the other two (p = 0.01−0.02), while the BGCs and GGCs have similar major axis distributions (p = 0.79). On the other hand, along the minor axis, the BGCs are the most extended among
the GC subgroups, having \( p \)-values of 0.07 and 0.04 for the comparison with GGCs and RGCs, respectively. The GGCs and RGCs could not be clearly distinguished with a \( p \)-value of 0.31.

In addition, we measured shape parameters such as ellipticity and position angle of the GC systems, assuming that the GCs constitute an ellipse. We used the dispersion ellipse of the bivariate normal frequency function of position vectors (Trumpler & Weaver 1953). The dispersion ellipse represents the contour at which the density is 0.61 times the maximum density of a set of points. This method has often been used for quantitative analysis of the two-dimensional distributions of galaxies in a galaxy cluster (Carter & Metcalfe 1980; Burgett et al. 2004; Hwang & Lee 2007) or GCs in a galaxy (McLaughlin et al. 1994; Hargis et al. 2011; Park & Lee 2013). We followed their analysis and derived the parameter uncertainties from 16th and 84th percentiles from the bootstrapping procedure with 1000 trials. We calculated the following five moments:

\[
\mu_{10} = \frac{1}{N} \sum_{i=1}^{N} X_i, \tag{1a}
\]
The position angle of the major axis is given by 
\[ \Gamma \]

Using these moments, the semimajor and semiminor axes of the dispersion ellipse, \( \Gamma_A \) and \( \Gamma_B \), are derived with the following equation:

\[
\begin{vmatrix}
\mu_{20} - \Gamma_A^2 & \mu_{11} \\
\mu_{11} & \mu_{02} - \Gamma_B^2
\end{vmatrix} = 0.
\] (2)

The position angle of the major axis is given by

\[
\theta = \cot^{-1} \left( \frac{-\mu_{02} - \Gamma_A^2}{\mu_{11}} \right) + \frac{\pi}{2},
\] (3)

and the ellipticity is

\[
e = 1 - \frac{\Gamma_B}{\Gamma_A}.
\] (4)

Figure 9(a) shows the dispersion ellipse for the entire GC sample confirmed in this study. Its position angle and ellipticity are \( \theta = 65^{\circ} \pm 5^{\circ} \) and \( e = 0.55 \pm 0.06 \). For comparison, we also derived the dispersion ellipses for GC subgroups, as shown in Figures 9(c)–(e). For the RGC system, we excluded an RGC with \( R > 20' \) that is an outlier of the overall distribution of the RGCs. The position angles of the dispersion ellipses for BGCs, GGCs, and RGCs are \( \theta = 65^{\circ} \pm 8^{\circ}, 65^{\circ} \pm 6^{\circ}, \) and \( 64^{\circ} \pm 12^{\circ}, \) respectively. They are consistent with each other and similar to the photometric position angle of the isophote of M85 at \( R_{\text{maj}} = 10' \) (\( 66^{\circ} \)). On the other hand, the ellipticity of the GGC system \( (e = 0.69 \pm 0.04) \) is 2\( \sigma \) higher than that of both the BGC and RGC systems \( (e = 0.45^{+0.11}_{-0.10} \) and \( 0.44^{+0.11}_{-0.13} \)), which means that the spatial distribution of the GGCs is more elongated than that of the BGCs and RGCs.

In addition to the differences in the spatial distributions of the GC subsystem, we examine their differences in the rotation features. Figure 11 shows the radial velocities of GCs as a function of position angle with the best-fit rotation curves. The GCs rotating along a given axis in the plane of the sky have radial velocities as a function of sinusoidal position angle. We measured the rotation amplitude and position angle of the rotation axis for the GC system by fitting the data with the following function:

\[
v_r(\Theta) = v_{\text{sys}} + (\Omega R) \sin(\Theta - \Theta_0),
\] (5)

where \( v_{\text{sys}} \) is the systemic velocity, \( \Omega R \) is the rotation amplitude, and \( \Theta_0 \) is the orientation of the rotation axis. We assumed the systemic velocity to be the radial velocity of the M85 nucleus, \( v_{\text{sys}} = 696 \text{ km s}^{-1} \), as derived in this study.

We fitted the data with this function for the entire GC system of M85 (Figure 11(a)). The rotation amplitude and the orientation of the rotation axis of the GC system are \( \Omega R = 80^{+52}_{-52} \text{ km s}^{-1} \) and \( \Theta_0 = 156^{+26}_{-26}^{\circ} \). The rotation axis is close to the minor axis of the stellar isophote at \( R_{\text{maj}} = 10' \). We calculated a rotation parameter, \( \Omega R/\sigma_{\text{r,cor}} \), defined as the ratio between the rotation amplitude and the rotation-corrected velocity dispersion. The entire GC system has a rotation parameter of \( \Omega R/\sigma_{\text{r,cor}} = 0.49^{+0.32}_{-0.23} \) with a rotation-corrected velocity dispersion of \( \sigma_{\text{r,cor}} = 163 \pm 11 \text{ km s}^{-1} \). This rotation parameter value is consistent with that of GC systems of massive early-type galaxies with luminosity similar to M85 (e.g., 0.45^{+0.25}_{-0.24} for M84 and 0.65^{+0.27}_{-0.22} for M60; Hwang et al. 2008; Alabi et al. 2016).

We found that the BGC and RGC systems show rotation properties significantly different from each other (Figures 11(d) and (j)). The RGC system shows a strikingly strong rotation feature with a rotation amplitude of \( \Omega R = 203^{+42}_{-42} \text{ km s}^{-1} \), which is almost a diskylike rotation. On the other hand, the rotation amplitude of the BGC system is close to zero with a large uncertainty (\( \Omega R = 50^{+58}_{-58} \text{ km s}^{-1} \)). The orientation of the rotation axis of the BGC system has a large uncertainty because its rotation feature is negligible (\( \Theta_0 = 162^{+12}_{-116}^{\circ} \)), but for the RGC system, it is precisely measured with a small uncertainty (\( \Theta_0 = 197^{+7}_{-7}^{\circ} \)). The rotation parameters of the BGC and RGC systems are \( \Omega R/\sigma_{r} = 0.30^{+0.38}_{-0.28} \) and \( \Omega R/\sigma_{r,cor} = 2.15_{-0.49}^{+1.65} \) respectively. We did not apply the rotation correction to the velocity dispersion for the BGC system because of its negligible rotation feature.

We did not derive the rotation parameters for the GGC system because most of the GGCs have radial velocities higher than the systemic velocity (\( \Delta v > 0 \text{ km s}^{-1} \)) and are concentrated only at position angles of \( 70^{\circ} \) and \( 240^{\circ} \) (Figure 11(g)).

We additionally divide the entire GC, BGC, GGC, and RGC samples into two groups, inner and outer systems, with a radial criterion of \( R = 6' \) and investigate their kinematics. The inner GC system has a rotation amplitude of \( \Omega R = 150^{+42}_{-42} \text{ km s}^{-1} \) and a rotation axis of \( \Theta_0 = 188^{+7}_{-13}^{\circ} \), which are marginally consistent with those derived from the small GC sample within \( R = 3' \) (Figure 11(b); Paper II). The rotation-corrected velocity distribution of the GC system shows that the spatial distribution of the GGCs is more elongated than that of the BGCs and RGCs.

Figure 10 (a) Cumulative major axis distance distributions of BGCs (dashed line), GGCs (solid line), and RGCs (dotted line). (b) Same as panel (a) but for minor axis distance.

\[
\begin{align*}
\mu_{01} &= \frac{1}{N} \sum_{i=1}^{N} y_i, \\
\mu_{20} &= \frac{1}{N} \sum_{i=1}^{N} x_i^2 - \left( \frac{1}{N} \sum_{i=1}^{N} x_i \right)^2, \\
\mu_{02} &= \frac{1}{N} \sum_{i=1}^{N} y_i^2 - \left( \frac{1}{N} \sum_{i=1}^{N} y_i \right)^2, \\
\mu_{11} &= \frac{1}{N} \sum_{i=1}^{N} x_i y_i - \frac{1}{N^2} \sum_{i=1}^{N} x_i \sum_{i=1}^{N} y_i.
\end{align*}
\]
dispersion for the inner GC system is $\sigma_{r,\text{cor}} = 132^{+10}_{-17}$ km s$^{-1}$, resulting in a rotation parameter of $\Omega R/\sigma_{r,\text{cor}} = 1.13^{+0.33}_{-0.27}$. This rotation parameter value is two times higher than that derived for the entire GC sample. This strong rotation of the inner GC system is mainly contributed by the RGCs. All RGCs are located within $R = 6'$ except for one, rotating strongly with a rotation amplitude of $\Omega R = 208^{+42}_{-42}$ km s$^{-1}$ and a rotation parameter of $\Omega R/\sigma_{r,\text{cor}} = 3.16^{+2.17}_{-0.53}$ (Figure 11(k)). On the other hand, the inner BGC system does not show any significant rotation features (Figure 11(e)). The inner BGC system has a rotation parameter of $\Omega R/\sigma_c = 0.41^{+0.04}_{-0.04}$, which is similar to the entire BGC system. Most of the inner GGCs are concentrated at a position angle of $240^\circ$, indicating a bulk motion (Figure 11(h)).

The outer GC system has a rotation amplitude of $\Omega R = 198^{+109}_{-78}$ km s$^{-1}$, which is comparable with the velocity dispersion of $\sigma_r = 177^{+17}_{-17}$ km s$^{-1}$. The rotation axis of the outer GC system is $\Theta_0 = 78^{+25}_{-13}$, which is totally different from that of the inner GC system (Figure 11(c)). This is because the fitting results are sensitive to the outer GGCs only concentrated at position angles of $70^\circ$ and $240^\circ$ (Figure 11(i)). If we only consider the outer BGC system, the rotation amplitude and orientation of the rotation axis are $\Omega R = 136^{+96}_{-56}$ km s$^{-1}$ and $\Theta_0 = 175^{+19}_{-49}$ (Figure 11(f)). The rotation parameter of the
outer BGC system ($\Omega R / \sigma_z = 0.75^{+0.32}_{-0.23}$) is higher than that of the inner BGC system but consistent within the uncertainties.

Additionally, we checked the possibility that there are any significant changes in the kinematic parameter measurements if the spatial elongations of the GC systems are considered in the fitting. Proctor et al. (2009) suggested a rotation model considering a rotation axis ratio,

$$v_{\text{mod}} = v_{\text{sys}} \pm \frac{v_{\text{rot}}}{\sqrt{1 + \left(\tan(\theta - PA_{\text{kin}}) / q\right)^2}},$$

where $PA_{\text{kin}}$ is the kinematic position angle defined as the angle from the north to the maximum receding part of the velocity map, and $q$ is the rotation axis ratio. The kinematic position angle $PA_{\text{kin}}$ is, by definition, different from the rotation axis orientation $\Theta_0$ in Equation (5) by 90°. This equation corresponds to the sinusoidal function we used if the axis ratio $q$ is equal to 1.

We adopted the photometric axis ratio of the isophotes at $R_\text{maj} = 10'' (q = 0.625)$, which is the most extreme case for the elongation. The fitting results are also plotted in Figure 11 for comparison. The rotation amplitudes derived with the axis ratio of $q = 0.625$ are slightly higher than the previous measurements. However, the mean difference is only 18 km s$^{-1}$, which is much smaller than the measurement uncertainties. The orientations do not show any significant differences either. Therefore, we conclude that our kinematic parameter measurements are irrelevant to the elongated spatial distributions of the GC systems.

### 3.3.3. Mean Radial Velocity and Velocity Dispersion Profiles

Figure 12(a) shows the mean radial velocities of GCs and Virgo dwarf galaxies in the survey region as a function of galactocentric distance from M85. We confirmed that the GGCs have mean radial velocities higher than the other GC subpopulations regardless of distance, as shown in Section 3.3.1. The mean radial velocity of four Virgo dwarf galaxies in the survey region is much higher than that of GCs.

In Figure 12(b), we display the distribution velocity profiles of the GCs confirmed in this study at $1'' < R < 23''/9$, the GCs studied in the previous study (Paper II), and the central stars at $R < 0''/6$ (Fisher 1997). The velocity dispersion of the inner BGCs is similar to that of the central stars. The outer BGCs with a mean galactocentric distance of $R = 12''/9$ have about 40 km s$^{-1}$ higher velocity dispersion than the inner BGCs, but this difference is within the uncertainties. The RGCs tightly follow the fitted rotation curve (Figure 11(j)), resulting in a dramatic change of the velocity dispersion after the rotation correction. The rotation-corrected velocity dispersion of the RGCs at $R = 3''/7$ ($\sigma_{\text{cor}} = 66^{+18}_{-22}$ km s$^{-1}$) is much lower than those of both the central stars and the BGCs. This indicates that the BGCs and RGCs trace different halo components of M85 (see Section 4.2).

### 4. Discussion

#### 4.1. Peculiar Motions of the M85 GC System

We confirm a strong rotation of the inner GC system of M85 in this study. This rotation was previously discovered from a small sample of 20 GCs in the inner region by Paper II. This study, based on the four times’ larger sample, found that this rotation is mainly due to the RGC system. The kinematic differences between the BGC and RGC systems have often been found in massive early-type galaxies (e.g., Lee et al. 2010; Pota et al. 2013). In general, the RGCs show a tighter correlation in the rotation velocity and velocity dispersion with those of the underlying stars of their host galaxies than the BGCs. This indicates that the RGCs were formed when the bulk of stars in their host galaxies were formed, but the BGCs have different origins, such as accretion from low-mass galaxies.

In the case of M85, the most interesting points found in this study are that (1) the RGC system strongly rotates and (2) its rotation feature does not even correspond to that of the central stars. The rotation feature of the stars in the central region ($R < 20''/9$) of M85 was derived in detail by ATLAS$^{3D}$ (Cappellari et al. 2011; Emsellem et al. 2011; Krajnović et al. 2011; see also an early measurement in Fisher 1997). The kinematic position angle of the central stars is $PA_{\text{kin}} = 190.5^{\circ} \pm 47.8$ (Krajnović et al. 2011). We derive the kinematic position angle of the RGC system to be $287^{\circ}$, which is almost perpendicular to that of the central stars. It indicates that the RGCs and central stars in M85 have undergone different experiences in their formation history. However, the stellar kinematics is derived only in the innermost region within $R \sim 20''/9$, while the RGCs are located in the outer region ($1'' < R < 20''/3$). Therefore, for a fair comparison, it is necessary to confirm the kinematic differences between the stars and the RGC system with a stellar kinematics study of the
outskirts of M85, which can be traced by planetary nebulae, for example.

In addition, we found that the GGCs constitute a stream aligned along the major axis of M85 out to $R = 31'$. The mean radial velocity of these GGCs, $v_r = 812^{+31}_{-26}$ km s$^{-1}$, is about $3\sigma$ higher than that of the other GC populations. This indicates that the GGCs may be a population infalling toward or outgoing from the M85 plane, which is associated with any previous merger or accretion event.

There have been several observational and simulation studies on GC streams in galaxies, suggesting that the GC streams are associated with stellar streams stripped from disrupting galaxies. For example, Foster et al. (2014) investigated the kinematics of GCs in the Umbrella Galaxy, NGC 4651, and showed that some GCs in the faint stellar substructures are remnants produced by a minor merger event with a 1:50 stellar mass ratio by comparing their kinematics with simulation data. Mackey et al. (2019) presented the kinematics of GCs in the outer halo of M31 and found that the GCs associated with the stellar halo substructures rotate with a perpendicular orientation with respect to the GCs in the smooth halo. They interpreted that these two distinct GC populations are considered to show the signatures from two different major accretion events. Recently, Alabi et al. (2020) studied the GCs in the spiral galaxy NGC 5907 lying in the stellar stream. They estimated a stellar mass of the disrupted galaxy that produced the stellar stream, using the mean metallicities of those GCs. In addition, Hughes et al. (2019) examined simulated galaxies and their GC systems from the E-MOSAICS project to understand the relation between the physical properties of GCs in stellar streams and their host progenitors.

Likewise, we try to seek any stellar substructure in M85 associated with the GGC stream to understand the origin of the GGCs. We could not detect any faint stellar streams along the direction where the GGCs are tightly aligned. Nevertheless, we found several shell structures that are perpendicular to that direction (Figure 4(c)). This shows a possibility that the GGCs are associated with any disrupted galaxies during minor merger events.

If the GGCs are an accreted population that originates from a single galaxy, we can infer the stellar mass of the progenitor from the mean metallicity of the GGCs. Peng et al. (2006) presented a relation between the mean metallicity of GCs and the stellar mass of their host galaxy: [Fe/H] = $(-5.250 \pm 0.156) + (0.409 \pm 0.014) \log (M_*)$. This iron abundance is calibrated to the metallicity scale of Zinn & West (1984), which corresponds to the total metallicity we derived in this study (Thomas et al. 2003). The GGCs have a mean metallicity of [Z/H] $\sim -0.91$. Using the above relation, the stellar mass of the disrupted galaxy that possibly hosted the GGCs is expected to be $4 \times 10^{10} M_\odot$. This value is similar to the stellar mass of the Milky Way, $(5 \pm 1) \times 10^{10} M_\odot$ (Bland-Hawthorn & Gerhard 2016).

### 4.2. Dark Matter Halo of M85

We found that the BGCs and RGCs show different behavior in their rotation-corrected velocity profiles (Figure 12). The velocity dispersion profile of the BGCs is approximately flat out to $R = 12'9$ (67 kpc), while the rotation-corrected velocity dispersion of the RGCs is much lower than that of the BGCs.

Park & Lee (2013) suggested that early-type galaxies have dual halos, a blue (metal-poor) halo and a red (metal-rich) halo, based on the geometric distinction between the BGC and RGC systems. According to the velocity dispersion profiles, we conclude that the red halo of M85 traced by the RGC system is truncated at $R \sim 3'-4'$, corresponding to $\sim 18$ kpc.

To investigate the extent of the M85 halo, we compare the kinematics of the GCs with that of the dwarf galaxies in the Virgo Cluster using the radial velocities of dwarf galaxies presented in the EVCC (Kim et al. 2014). There are only four Virgo dwarf galaxies in our survey region, and all of them have radial velocities higher than the M85 nucleus (Figure 7). The mean radial velocity and radial velocity dispersion of these dwarf galaxies are $v_r = 1113 \pm 158$ and $\sigma = 316 \pm 112$ km s$^{-1}$.

The kinematics of the M85 GCs is totally different from that of the Virgo dwarf galaxies in the survey region in terms of both the mean velocity and velocity dispersion. This indicates that the gravitational potentials governing these two populations are different. The mean radial velocity and velocity dispersion of the Virgo dwarf galaxies at the same cluster-centric distance as M85 ($\sim 6'$) are derived to be $\overline{v} = 1107$ and $\sigma = 327$ km s$^{-1}$, respectively (Kim et al. 2014). The dwarf galaxies in our survey region have kinematics similar to other dwarf galaxies in Virgo despite the small sample. Therefore, we conclude that the dwarf galaxies in our survey region follow the cluster potential, while the blue halo traced by the BGCs is controlled by the distinguishable galaxy potential.

#### 4.3. Dynamical Mass in M85

We estimated the dynamical mass of M85 based on the kinematics of the GC system. The M85 GCs clearly show different kinematics according to their colors. We only used the BGC system to derive the dynamical mass of M85 because it is a pressure-supported system that shows a negligible rotation feature.

We estimate the pressure-supported mass of M85 using the tracer mass estimator (TME) from Watkins et al. (2010). The TME is a robust method to estimate the enclosed mass based on the projected positions and line-of-sight velocities of tracers. The enclosed mass based on the TME method is given by

$$M_\rho = \frac{C}{GN} \sum_{i} (v_{los,i} - v_{sys})^{2} R_i^\alpha,$$

where $N$ is the number of tracers, $v_{los,i}$ is the rotation-corrected radial velocity of a given tracer, $v_{sys}$ is the systemic velocity, $\alpha$ is the power-law slope of the underlying gravitational potential profile, and $R_i$ is the projected galactocentric distance of the tracers. The constant $C$ is defined as

$$C = \frac{\alpha + \gamma - 2\beta}{L_{\alpha,\beta}} r_{out}^{-\alpha},$$

where $\gamma$ is the power-law slope of the volume number density profile of the tracers, $\beta$ is the anisotropy parameter ($\beta = 1 - \sigma_\alpha^2/\sigma_\phi^2$), $r_{out}$ is the deprojected radius of the outermost tracer, and

$$L_{\alpha,\beta} = \frac{\pi^{1/2} \Gamma(\frac{\alpha}{2} + 1)}{4\Gamma(\frac{\alpha}{2} + \frac{5}{2})} [\alpha + 3 - \beta(\alpha + 2)].$$

We adopted a $\gamma$ parameter of 3.28 from the number density profile of BGCs based on a wide-field photometric survey.
given by Paper 1. The $\alpha$ parameter is zero for the isothermal dark matter halo, which shows a flat rotation curve and 0.55 for the NFW dark matter profile (Navarro et al. 1996; Watkins et al. 2010). The $\beta$ parameter is zero for isotropic orbits and 1 for purely radial orbits. We estimated the dynamical mass uncertainty from the bootstrapping method. We randomly selected 41 objects from the BGCs allowing replacement and calculated the dynamical mass with their radial velocities based on the TME method. In this process, the radial velocities and the slope of the number density profile of BGCs are also randomly chosen within their uncertainties. We repeated this process 1000 times and found the 16th and 84th percentiles of the measurements. We adopted the differences between the mass derived with the actual data and the 16th/84th percentiles as the uncertainty.

We estimate the dynamical mass of M85 enclosed within $R = 124$ kpc to be $M_{\text{TME}} = (3.8 \pm 0.6) \times 10^{12} M_{\odot}$, assuming the isothermal dark matter halo and isotropic orbits. Previously, Sansom et al. (2006) derived the mass of M85 enclosed within $R = 10$ kpc from X-ray hot gas observations, which is $2 \times 10^{12} M_{\odot}$. In addition, Babyk et al. (2018) estimated the total mass of M85 to be $4 \times 10^{12} M_{\odot}$ by extrapolating the total mass profiles out to $5 R_e$ (37 kpc). These measurements are 10–20 times smaller than the dynamical mass derived in this study. This is because M85 lacks hot gas, compared to other galaxies with similar luminosity (Sansom et al. 2006), and our radial coverage is much larger than that of the previous studies.

We compare the dynamical mass of M85 to that of early-type galaxies with similar luminosity as M85. Alabi et al. (2016) presented dynamical masses of 23 early-type galaxies derived with their GC kinematics. Among them, we selected seven galaxies with $K$-band magnitudes of $-25.5 \, mag < M_K < -24.5 \, mag$, which are similar to that of M85 ($M_K = -25.1 \, mag$; Jarrett et al. 2003). These galaxies have pressure-supported masses ranging from $6.5 \times 10^{11}$ to $3.26 \times 10^{12} M_{\odot}$ with radial coverage of $R < 9–21$ effective radii ($R_e$). We derive the enclosed mass of M85 within $R = 14 R_e$ comparable to the coverage for other galaxies, adopting the effective radius of M85, $R_e = 102''28$ (Kormendy et al. 2009). Compared to the other galaxies with similar luminosity, M85 has a larger dynamical mass, which indicates the existence of a large amount of dark matter in M85 within $R = 14 R_e$.

5. Summary

We present a spectroscopic study of GCs in the merger remnant galaxy M85 using the MMT/Hectospec. We identify 89 GCs in the radial range of $1.5 < R < 31'$ based on radial velocity measurements. We divided the confirmed GCs into three groups according to their colors: 41 BGCs with $0.6 < (g - i)_0 < 0.7$, 32 GGCs with $0.7 < (g - i)_0 < 0.8$, and 16 RGCs with $0.8 < (g - i)_0 < 1.0$. The GC subpopulations show notable differences in their spatial distribution, kinematics, and mean metallicities. We could not find any significant differences in their ages, showing that all GC subpopulations are as old as 10 Gyr, on average. The detailed properties of each GC subpopulation are summarized as follows.

1. The BGC system has a mean radial velocity of $\bar{v} = 727 \pm 34 \, km \, s^{-1}$, consistent with the systemic velocity of M85 ($v_{sys} = 696 \, km \, s^{-1}$), and shows little rotation. The velocity dispersion of the BGCs is $\sigma = 168^{+14}_{-13} \, km \, s^{-1}$. The BGCs are the most metal-poor population among all GC subpopulations in M85, having a mean metallicity of $[Z/H] = -1.49$.

2. Most of the GGCs have radial velocities much higher than the systemic velocity of M85, with a mean radial velocity of $\bar{v} = 812^{+20}_{-27} \, km \, s^{-1}$. They constitute a stream out to $R = 31'$ along the major axis of the outer isophotes of M85. The GGCs have a mean metallicity of $[Z/H] = -0.91$, which is between that of the BGCs and RGCs.

3. The mean radial velocity of the RGCs is $\bar{v} = 704 \pm 37 \, km \, s^{-1}$, consistent with the systemic velocity. The RGC system shows a disklike strong rotation with a rotation parameter of $\Omega R/\sigma_{\text{circ}} = 2.15$. The rotation-corrected velocity dispersion of the RGCs within $R = 6'$ is $\sigma_{\text{circ}} = 66 \, km \, s^{-1}$, much smaller than that of the BGCs and the central stars. The mean metallicity of the RGCs is $[Z/H] = -0.45$, which is the highest among those of all GC subpopulations in M85.

These differences in the kinematics of the GC subpopulations imply that they have different formation and evolution histories. The BGCs in M85 have kinematic properties similar to those in other massive early-type galaxies, which are expected to be accreted from the disrupted dwarf galaxies. The metal-poor population of the BGCs also supports this scenario. On the other hand, the GGCs and RGCs in M85 have peculiar kinematics that cannot be explained by the typical GC formation scenarios. The GGCs may be a population accreting to or escaping from the M85 plane, and the RGCs may be a remnant produced by recent off-center major merging events. Comparing their spatial distribution and kinematics with those of planetary nebulae in the outer stellar light would be helpful to understand the origin of these GCs.

In addition, we investigate the extent and dynamical mass of the M85 halo using the GC kinematics. The mean radial velocity and velocity dispersion of the GCs in M85 are different from those of the Virgo dwarf galaxies around M85. Especially, the low velocity dispersion of the RGC system indicates a truncation of the red halo of M85. The BGCs are distributed out to $R = 23'9$, having a velocity dispersion lower than that of the Virgo dwarf galaxies. Therefore, we conclude that M85 has a distinguishable galaxy potential at least out to $R = 23'9$ corresponding to 124 kpc. From the kinematics of the pressure-supported BGC system, we derive the dynamical mass of M85 to be $M_{\text{TME}}$ ($R < 124$ kpc) = $(3.8 \pm 0.6) \times 10^{12} M_{\odot}$, assuming the isothermal dark matter halo and isotropic orbit.
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