Star Clusters in the Elliptical Galaxy NGC 4589 Hosting a Calcium-rich SN Ib (SN 2005cz)

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Abstract

NGC 4589, a bright E2 merger-remnant galaxy, hosts the peculiar fast and faint calcium-rich SN Ib SN 2005cz. The progenitor of Ca-rich SNe Ib has been controversial: it could be (1) a young, massive star with $6–12 M_\odot$ in a binary system, or (2) an old, low-mass star in a binary system that was kicked out from the galaxy center. Moreover, previous distance estimates for this galaxy have shown a large spread, ranging from 20 to 60 Mpc. Thus, using archival Hubble Space Telescope/ACS F435W, F555W, and F814W images, we search for star clusters in NGC 4589 in order to help resolve these issues. We find a small population of young star clusters with $25 < V \leq 27$ ($-7.1 < M_V \leq -5.1$) mag and age $<1$ Gyr in the central region at $R < 0.15$ (3.8 kpc), thus supporting the massive-star progenitor scenario for SN 2005cz. In addition to young star clusters, we also find a large population of old globular clusters. In contrast to previous results in the literature, we find that the color distribution of the globular clusters is clearly bimodal. The turnover (Vega) magnitude in the V-band luminosity functions of the blue (metal-poor) globular clusters is determined to be $V_0(\text{max}) = 24.40 \pm 0.10$ mag. We derive the total number of globular clusters, $N_{\text{GC}} = 640 \pm 50$, and the specific frequency, $S_N = 1.7 \pm 0.2$. Adopting a calibration for the metal-poor globular clusters, $M_V(\text{max}) = -7.66 \pm 0.14$ mag, we derive a distance to this galaxy: $(m - M)_0 = 32.06 \pm 0.10$ (run + 0.15 (sys)) $(d = 25.8 \pm 2.2$ Mpc).

Key words: galaxies: distances and redshifts – galaxies: elliptical and lenticular, cD – galaxies: individual (NGC 4589) – galaxies: star clusters: general – ISM: supernova remnants

Supporting material: machine-readable table

1. Introduction

SNe Ib are the remnants of the collapsed core of massive WC Wolf-Rayet stars that lost most of their outer hydrogen envelope (so they are sometimes called thin-striped core-collapse SNe; Smartt 2009). Their spectra show a distinguishable He I 5876 Å line but little sign of silicon lines. Recently, a new type of SN Ib called Ca-rich SNe Ib has been discovered in NGC 1032 (Perets et al. 2010). The spectra of the early phase of Ca-rich SNe Ib show He I lines, while the spectra of their late phase show Ca lines. Ca-rich SNe Ib are much fainter and show a faster decline rate in their light curves compared to normal SNe Ib (see the review by Taubenberger 2017, in his Section 5).

Ca-rich SNe Ib host many interesting properties. First, about 50% of all Ca-rich SNe Ib are found in E or S0 galaxies (Perets et al. 2010; Kasliwal et al. 2012; Taubenberger 2017). It is difficult to reconcile this fact with the conventional concept of massive stars being the progenitors of normal SNe Ib. Second, they are often found much farther from the center of their host galaxies, and they are found even in the intracluster or intragroup region, so they are sometimes called homeless SNe (Kasliwal et al. 2012; Foley 2015; Lunnan et al. 2017). Third, Lyman et al. (2016) found no evidence of globular clusters or dwarf galaxies at the position of known Ca-rich SNe in the Hubble Space Telescope (HST) images, and they concluded that the progenitors of these Ca-rich SNe must have come from somewhere else, offset from the current SN position.

These results have made the origin of Ca-rich SN Ib progenitors controversial, whether it is (1) a young, massive star with $6–12 M_\odot$ in a binary system (Kawabata et al. 2010; Gvaramadze et al. 2017; Moriya et al. 2017), or (2) an old, low-mass star in a binary system that was kicked out from the galaxy center or elsewhere (Perets et al. 2011; Foley 2015; Lyman et al. 2016).

One of the most popular targets to study the progenitors of Ca-rich SNe Ib has been NGC 4589 hosting SN 2005cz (Kawabata et al. 2010; Perets et al. 2011; Foley 2015). NGC 4589 is a bright, X-ray-emitting elliptical galaxy with a LINER nucleus. It is the brightest member of a loose group of galaxies (group no. 107 in Geller & Huchra 1983). The red integrated color ($(V - I) = 1.18$) and the relatively faint $F160W$-band absolute magnitude of the surface brightness fluctuation (SBF) of NGC 4589 indicate that this galaxy is dominated by old stellar populations (Jensen et al. 2003, see their Figures 2–4). Basic properties of NGC 4589 are summarized in Table 1.

However, the distance to NGC 4589 is still uncertain. Previous distance estimates for this galaxy show a large spread (ranging from 20 to 60 Mpc), though distance estimates based on the SBF method show a much smaller spread (de Vaucouleurs & Olson 1984; Faber et al. 1989; Willick et al. 1997; Tonry et al. 2001; Jensen et al. 2003; Theureau et al. 2007; Blakeslee et al. 2010). Therefore, in this study, we estimate the distance to this galaxy using the luminosity functions of the globular clusters (GCLFs) detected in this galaxy (Harris 2001; Richtler 2003; Di Criscienzo et al. 2006; Rejkuba 2012).

More interestingly, observations of NGC 4589 show several peculiar features (Hakobyan et al. 2008). It hosts a dust disk that is aligned along the minor axis, and it is rotating fast around its major axis (Moellenhoff & Bender 1989). Ionized gas emission is detected along the minor axis at $R < 20\prime$ from the galaxy center. Moellenhoff & Bender (1989) found that both gas and stellar components show strong rotation with
complex kinematics. They suggested that a gas-rich galaxy fell into NGC 4589 and formed a rotating dust disk in the inner region of the galaxy, and that NGC 4589 is in an advanced state of merging. A small amount of H$_2$ gas, 9.1 $\times$ 10$^5$ $M_{\odot}$, was detected in this galaxy from CO observations (Sofue & Wakamatsu 1993). Polycyclic aromatic hydrocarbon (PAH) emissions at 11.3 $\mu$m were detected in the position of the dust lanes, and far-IR and 17 $\mu$m PAH emissions were found in the more extended regions of NGC 4589 (Kaneda et al. 2008, 2010). Kaneda et al. (2010) suggested that 11.3 $\mu$m PAH features may be due to the gas brought in by an early merger, and the far-IR emission and 17 $\mu$m PAH features are relics of a later merger.

If NGC 4589 had a recent wet merger, then there may be a population of young star clusters that can provide the massive-star progenitor for SN 2005cz. Motivated by this idea, we search for star clusters in NGC 4589 using HST images in the archive, and we investigate their properties to tell whether any young to intermediate-age clusters exist or not in this galaxy.

To date, there is only one published paper on the star clusters in NGC 4589. Kundu & Whitmore (2001) presented $V$ photometry of bright globular clusters with 21 $< V < 24.5$ mag in NGC 4589 based on shallow HST/WFPC2 F555W and F814W images. They found no bimodality in the color distribution of these globular clusters, which is in contrast to the cases of other bright elliptical galaxies that show mostly strong bimodality (Brodie & Strader 2006; Harris et al. 2017 and references therein). This may be an intrinsic nature of NGC 4589 or due to the shallow photometry in their study. Thus, nothing is known about any of the young star clusters in this galaxy.

This paper is organized as follows. Section 2 describes how we select star clusters from the HST images of NGC 4589. In Section 3, we present photometric properties of the detected star clusters, as well as their spatial and radial distributions. We derive their GCLFs and use them to determine the distance to NGC 4589. In Section 4, we discuss the origin of SN 2005cz in relation to our results, compare our GCLFs with the previous study, and compare our distance estimate with previous distance estimates. Finally we summarize the main results in the conclusion.

### 2. Data Reduction and Star Cluster Selection

#### 2.1. Data

We used Advanced Camera for Surveys (ACS) images for NGC 4589 from the HST archive (PI: Smartt, ID: 10498). The exposure times are 1500 s for F435W, 1500 s for F555W, and 1600 s for F814W. We combined individual images of NGC 4589 within the same filter using AstroDrizzle (Gonzaga et al. 2012). The image scale of the combined images is 0.0605 per pixel.

Figure 1 displays a color image of the HST field, the location of which is marked in the WISE-W1 (3.6 $\mu$m) image in the upper left. SN 2005cz is located at $\sim$13$^\prime$ (1.6 kpc for the adopted distance of 25.8 Mpc here) southeast from the galaxy center, as marked by the circle close to the galaxy center. In the upper right, we display a zoomed-in image of the central region of NGC 4589 from which the galaxy light model was subtracted. Note the presence of dust lanes that are perpendicular to the major axis (which is almost horizontal in the image) in the central region. A zoomed-in image of a southern field in the lower left shows two compact sources, which are star cluster candidates in NGC 4589 (the red bright source below is a foreground star).

#### 2.2. Data Reduction

We reduced the data following the procedures used in the study of star clusters in Coma galaxies by Lee & Jang (2016). We derived model images of the galaxy light using IRAF/
ellipse after masking all of the bright sources except NGC 4589. Then we subtracted the model galaxy images from the drizzled images for better source detection. The resulting images are used for source detection and photometry with DAOPHOT (Stetson 1994). A master source list was made from the F814W image with a detection threshold of 5σ.

Effective radii of typical globular clusters are 2–3 pc, so globular clusters at the distance of NGC 4589 are expected to appear as point sources or as slightly resolved sources in the HST/ACS images with an image scale of ~6 pc per pixel. The magnitude difference between small and large apertures is one of the most effective central concentration parameters to distinguish between point sources and extended sources (Whitmore et al. 1999; Peng et al. 2011), as shown in the study of star clusters using the HST images for Coma galaxies in Lee & Jung (2016). We calculated the values of the F814W magnitude concentration parameter for the detected sources using aperture magnitudes with radii of 1.5 pixels and 3.0 pixels, C(1.5 pix–3.0 pix).

We derived F814W aperture correction values for the sources including star cluster candidates following the method used in Lee & Jung (2016). The steps are as follows. First, we selected isolated bright sources with a varying range of concentration parameters. For these selected sources, we calculated the value of the magnitude difference between the aperture radii of 10 and 4 pixels, Δ(10 pix–4 pix). From linear fitting, we obtain Δ(10 pix–4 pix) = −0.56Δ(1.5 pix–3.0 pix) + 0.175 with rms = 0.028. We applied this aperture correction to derive a magnitude for the aperture radius of 10 pixels (=0.75). Then we derived F435W and F555W magnitudes from F814W magnitudes using the 4 pixel radius colors of the sources, for example, F555W (10 pix) = F814W (4 pix) + Δ(10 pix–4 pix) + (F555W–F814W) (4 pix). Finally, we applied a further aperture correction for radii = 0.85 to infinity using the values provided by the STScI (−0.106 mag for F435W, −0.096 mag for F555W, and −0.098 mag for F814W).

If we use aperture corrections for radii = 4–10 pixels derived for each band and apply them to obtain their colors, the resulting colors will have larger errors. The method adopted in this study is valid only if there is no color gradient in the 4–10 pixel region of the sources.

According to the enclosed energy distribution of point sources in the ACS data listed in Table 3 of Sirianni et al. (2005), the stellar fluxes within a certain radius have a slight variation depending on the filter. The fractions of stellar flux within a 4 pixel radii aperture in this table are 0.832, 0.843, and 0.833 for F435W, F555W, and F814W, respectively. These flux variations lead to very small color differences: Δ(F435W − F555W) = +0.014 mag (=−2.5 × log10(0.832/0.843)), and Δ(F555W − F814W) = −0.013 mag (=−2.5 × log10(0.843/0.833)). We ignored this small color correction before deriving the total magnitudes of the F555W and F814W bands.

The instrumental magnitudes in the HST system were converted to the standard calibrated BVI magnitudes in the Johnson–Cousins system using the information in Sirianni et al. (2005). The photometric zero points (c0) and color terms (c1) we used are as follows: c0 = 25.842 and c1 = −0.089 for F435W, c0 = 25.704 and c1 = −0.054 for F555W, and c0 = 25.495 and c1 = −0.002 for F814W. Transformation uncertainties are estimated to be ±0.02 mag in each band.

However, we noted that the photometric zero points for ACS/WFC have a slight dependence on time. The photometric transformation in Sirianni et al. (2005) was made using HST data for NGC 2419 and 47 Tuc taken in 2002, but observations for NGC 4589 were obtained in 2006. According to the STScI web page, the photometric zero points for F435W, F555W, and F814W in 2006 are on average 0.03 mag smaller than those in 2002. This variation in zero points could lead to larger systematic uncertainties in the transformation. We, therefore, adopt a conservative value of ±0.03 mag for the final uncertainty associated with the photometric transformation. In this study, we use Vega magnitudes and use the “0” subscripts for extinction-corrected quantities in the following analysis.

2.3. Size Estimation

We estimated the effective radii of bright sources with V ≤ 25 using the ISHAPE program (Larsen 1999). A point-spread function (PSF) modeling is one of the most important steps in the ISHAPE run. In HST data, synthetic PSFs (e.g., TinyTim PSFs; Krist et al. 2011) are optimized for individual frame images. Individual frame images (“_flc.fits”) have a strong geometric distortion, so using synthetic PSFs may not be the best choice (see the ISHAPE manual for details). For this reason, many previous studies used drizzled images, which are geometric-distortion-corrected and mostly coadded images, with empirical PSFs. However, modeling empirical PSFs is not always easy. Most extragalactic HST fields have a limited number of isolated bright stars, and they have a stellar spectral energy distribution (SED) different from target star clusters. Selecting a clean point source is also not easy because of the presence of blended stars, compact star clusters, and compact background galaxies. All of these difficulties are possible sources of uncertainties in the size estimation.

Thus we adopted an alternative approach to solving most of the problems mentioned above by using TinyTim PSFs with a single-drizzled image. The steps are as follows. We generated 400 TinyTim PSFs and placed them onto chip 1 (science extension 4) and chip 2 (science extension 1) of an flc image. We set a spectral type of K4V for the PSFs, similar to those of old globular clusters. We then drizzled this single-frame flc image. The output image is corrected for the geometric distortion but is not coadded. This image was used for generating the input PSFs using IRAF/DAOPHOT for the ISHAPE run. The drizzled images we used for the aperture photometry are coadded, so they are not ideal for size estimation based on the modeled PSFs.

We prepared F814W-band single-drizzled images (from one flc image) of the original NGC 4589 data and used them for size estimation. We used a King model with a concentration parameter of 30 to fit sources. The mean size for each stellar object was computed from individual frame measurements with a median-based σ-clip algorithm set at 2σ. We assigned the standard deviation of the clipped size values for size estimation errors. Angular radii were converted to linear radii, adopting a distance of 25.8 Mpc as derived in the following section.

2.4. Star Cluster Selection

Before selecting star cluster candidates in the list of the detected sources, we visually inspected the images of all detected sources with V(total) ≤ 27 mag and removed artifacts, blended sources, and sources with irregular morphology. We set this magnitude limit by considering the photometric depth...
needed to cover a much fainter magnitude than the peak of the GCLF and the capacity of our visual inspection. Visual inspection of the images becomes difficult for the fainter sources. We selected 745 out of 2973 inspected sources. This is the star cluster search sample.

We prepared another sample that includes only bright sources with $V \leq 25$ mag. We selected 452 out of 546 inspected sources with $V \leq 25$ mag. The sources in the bright sample have smaller photometric errors and are better for analysis than the fainter sources. We use this bright sample for the following analysis of structural parameters and colors of the sources.

Figure 2(a) displays $V$-band magnitudes versus $C$ for the selected bright sources with $V \leq 25$ mag. We divided the detected sources according to their color: the blue sources with $(B - V) \leq 0.5$, the globular cluster-like sources with $0.6 < (B - V) \leq 1.2$, and the red sources with $(B - V) > 1.3$. We adopted the color intervals for globular cluster selection based on the color distributions of Milky Way globular clusters (Harris 1996). We chose our color selection intervals for the blue and red sources to have the cleanest and least-contaminated sample of blue sources and red sources. Figures 2(b) and (c) display, respectively, the DAOPHOT sharpness parameter values and effective radii versus $C$. In Figure 2(d), we plotted the $C$ number distributions for these sources.

Several features are noted in Figure 2. First, there is a strong concentration of sources at $C \approx 0.5$–0.7. They are dominated by sources with globular cluster-like colors. Most of these sources are slightly resolved sources. Thus these sources are mostly globular clusters in NGC 4589. The median value of the effective radii of the globular clusters in NGC 4589 in this study is 2.5 pc (rms = 1.7 pc), which is similar to the value for the Milky Way globular clusters, 3 pc (Harris 1996). Second, the red sources show a narrow vertical plume at $C \approx 0.5$ in Figure 2(a). The sources with $C \approx 0.5$ have a median DAOPHOT sharpness value of 0.004 (rms = 0.072), which shows that they are point sources. These point sources are dominated by red dwarf stars in the Milky Way. Third, the number of blue sources is small. Blue sources show a broad distribution of $C$, and most of them have, on average, much larger $C$ values and fainter magnitudes than the other two groups. They are considered to be mostly background galaxies.

Fourth, the values of sharpness and effective radii show a strong correlation with the values of $C$. This shows that $C$ is a very effective parameter to distinguish point sources and extended sources.

We select, as the initial star cluster candidates, the slightly extended sources with $0.52 < C \leq 0.8$ (referred to as the compact sources hereafter) and the point sources with $C \leq 0.52$. The $C$ distribution of the red sources, which are mostly foreground stars, shows a peak at $C \approx 0.5$ and declines to a zero value at $C > 0.52$. On the other hand, the $C$ distribution of the globular cluster-like sources shows a peak at $C \approx 0.6$ and declines to a zero value at $C > 0.8$. Therefore we chose $0.52 < C \leq 0.8$ to have the cleanest and least-contaminated GC sample. The selected cluster candidates are composed of mainly slightly resolved star clusters and a small number of point sources. The selected point sources are considered to be mostly unresolved star clusters or stars.

In Table 2 we present a catalog of the star clusters in NGC 4589, including their $BVI$ photometry and effective radii.

### 2.5. Completeness Tests

We estimated the completeness of our photometry using artificial sources. We generated images of the star cluster-like sources with $0.55 < C \leq 0.65$. We assumed that the luminosity function of the sources is Gaussian with a peak at a $V$-band total magnitude of 24.5 mag and a width of 1.0 mag, similar to the luminosity function of the globular clusters in NGC 4589 derived in the following section. We adopted four colors for the artificial sources: $(B - V) = 0.2$ and $1.4$ ($(V - I) = 0.7$ and $1.4$), which are close to the mean colors of the young and very red star clusters, and $(B - V) = 0.75$ and $0.95$ ($(V - I) = 1.0$ and $1.2$), which are close to the mean colors of the blue and red globular clusters.

We injected 250 artificial clusters onto the original image to create a test image. We repeated this procedure 1000 times and prepared 1000 test images. We set the artificial sources to have a centrally concentrated spatial distribution. The central region at $R < 0.1$ mag is masked out. We analyzed these test images using the same procedures as used for the original images in order to estimate the recovery rates, that is, the ratios of the number of recovered sources with respect to the number of input sources.
Figure 3 displays the results of the artificial source experiments. The recovery rates for $V = 27$ mag are 52%, 61%, 66%, and 68% for $(B-V) = 0.7, 1.0, 1.2,$ and $1.4$ $(B-V) = 0.2, 0.75, 0.95,$ and $1.4$, respectively. Red circles with error bars in the middle and bottom panels denote the mean values with $\pm 1\sigma$ for given magnitudes. The input sources have a magnitude range of $21 < V < 28$ mag (corresponding to $20 < I < 27$ mag for $(V-I) = 1.0$).

Table 2

| ID   | R.A. (J2000) | Decl. (J2000) | $V$ (mag) | err($V$) | $(B-V)$ | err$(B-V)$ | $(V-I)$ | err$(V-I)$ | $r_{	ext{eff}}$ (pc) | err$y_{	ext{eff}}$ (pc) | $C_I^a$ | Remarks$^b$ |
|------|--------------|---------------|-----------|----------|----------|------------|----------|------------|----------------|----------------|--------|-------------|
| 1    | 189.530546   | 74.171445     | 26.002    | 0.194    | 1.100    | 0.350      | 0.802    | 0.162      | ...          | ...            | 0.705  | ...         |
| 2    | 189.523901   | 74.168912     | 26.014    | 0.134    | 0.560    | 0.191      | 1.332    | 0.119      | ...          | ...            | 0.691  | ...         |
| 3    | 189.519277   | 74.169479     | 23.733    | 0.018    | 1.394    | 0.046      | 2.227    | 0.017      | 0.02         | 0.05           | 0.475  | ...         |
| 4    | 189.518752   | 74.178858     | 24.658    | 0.050    | 0.748    | 0.069      | 0.942    | 0.041      | 0.65         | 1.05           | 0.603  | GC          |
| 5    | 189.513980   | 74.171037     | 25.916    | 0.198    | 0.067    | 0.141      | 0.256    | 0.143      | ...          | ...            | 0.705  | ...         |

Notes.
$^a$ Concentration parameters derived from the F814W image.
$^b$ Globular cluster candidates are marked by “GC.”
(This table is available in its entirety in machine-readable form.)

Figure 3 displays the results of the artificial source experiments. The recovery rates for $V = 27$ mag are 52%, 61%, 66%, and 68% for $(V-I) = 0.7, 1.0, 1.2,$ and $1.4$, respectively. The mean values of the input magnitudes minus the output magnitudes are smaller than 0.03 mag for $V \leq 26.5$ mag and $I \leq 25.5$ mag.

In Figure 4 we plot the V-band 50% completeness level as a function of galactocentric distance. The 50% recovery magnitudes become fainter as galactocentric distance increases. For $(V-I) = 1.0$, the 50% recovery magnitude is $V = 26.2$ mag at $R = 0\farcs3$, $V = 27.3$ mag at $R = 0\farcs9$, and $V \approx 27.5$ at $R = 1\farcs3–2\farcs6$.

3. Results

3.1. Color–Magnitude Diagrams of the Star Clusters

We display the color–magnitude diagrams (CMDs) of the point sources ($C \leq 0.52$), the compact sources ($0.52 < C \leq 0.8$), and the extended sources ($0.8 < C \leq 1.0$) with $V \leq 27$ mag in Figure 5. The error bars in the left side represent...
median photometric errors for given magnitudes derived from the photometry of all the measured sources. We also plotted Padova simple stellar population (SSP) models for solar metallicity (cyan lines) and 0.1 $Z_{\odot}$ (blue lines) with cluster mass $M/M_{\odot} = 10^{3.5}$ and $10^{4.5}$ (Girardi et al. 2000).

These CMDs show several notable features. First, the most distinguishable feature is a broad vertical branch at $0.6 < (B - V) < 1.2$ ($0.8 < (V - I) < 1.4$), the brightest of which reaches $V \approx 21$ mag ($I \approx 20$ mag). This branch consists of a dominant population of compact sources and a small number of point sources. The colors of these sources are similar to those of typical globular clusters. Thus the sources in this branch are mostly considered to be globular clusters in NGC 4589. The branch also contains a small population of extended objects whose colors are numerically not much different from those of the globular clusters. They are mostly background galaxies.

Second, there is a small population of blue compact sources at $(B - V) \leq 0.5$ ($(V - I) \leq 0.7$), which are bluer than the blue limit for the globular clusters. They are mostly fainter than $V = 25$ mag ($I = 24$ mag), so they are much fainter than the majority of the globular clusters. These sources can be either young star clusters in NGC 4589 or background galaxies. To investigate their nature further, we inspect their spatial and radial distributions in the following sections.

Third, there is a narrow vertical sequence of very red point sources with $21 < V \leq 25$ mag at $1.3 < (B - V) \leq 1.6$. They have $(V - I)$ colors of 1.5–3.0, as seen in Figure 6, and many of them present in the $(B - V)$ panel are outside the plotted range for the $(V - I)$ plot. They are mainly red dwarf stars in the Milky Way.

Fourth, extended sources show a much broader color distribution and fainter magnitudes compared with compact sources. The number of extended sources is much smaller than that of compact sources, and the spatial distribution of extended sources appears to be uniform.

### 3.2. Color–Color Diagrams of the Star Clusters

Figure 6 shows the color–color diagram of the point sources, the compact sources, and the extended sources. The left and right panels display the sources with $V \leq 25$ mag ($M_V \leq -7.1$ mag) and those with $V \leq 27$ mag ($M_V \leq -5.1$ mag), respectively. We also plotted Padova evolutionary tracks for the SSPs with solar metallicity (cyan lines) and 0.1 $Z_{\odot}$ (blue lines) and the 12 Gyr isochrones for [Fe/H] = −2.3 to +0.0 (red lines). The solid circles along the evolutionary track represent the age, $10^{7}$, $10^{8}$, $10^{9}$, and $10^{10}$ yr. In this diagram, the globular clusters are located along the 12 Gyr isochrones for a large range of metallicities, showing that they are indeed old globular clusters with a large range of metallicities.

The blue sources with $(B - V) < 0.5$ and $(V - I) < 1.0$ are located around the SSP models with age <1 Gyr, but with a large scatter. The mean photometric errors of these blue sources are $\text{err}(B - V) = 0.13$ $\text{err}(V - I) = 0.12$ for $25 < V \leq 26$ mag and $\text{err}(B - V) = 0.25$ $\text{err}(V - I) = 0.21$ for $26.0 < V \leq 27$ mag. Therefore, the large scatter in color is mainly due to photometric errors.

There are a small number of extended sources that overlap the color–color sequence of globular clusters. One of the extended sources has $V = 21.6$ mag, as bright as the brightest globular clusters, and the rest are more than two magnitudes fainter than this. The effective radius of the brightest extended source is 7.6 pc, smaller than the values for ultracompact dwarfs (UCDs), so it is considered to be an extended bright globular cluster. Thus none of them are found to be UCDs.
3.3. Color Distributions of the Globular Clusters

Figure 7 shows the color distributions of the bright star cluster candidates with $C < 0.8$ and $V < 25$ mag at $0''2 < R < 2'\prime$ in NGC 4589. The most prominent feature in this figure is due to globular clusters in NGC 4589. The color distributions of these globular clusters show two peaks in both $(B - V)$ and $(V - I)$ colors, clearly suggesting that they are bimodal, as often seen in other early-type galaxies.

We applied a Gaussian mixture modeling (GMM) test (Muratov & Gnedin 2010) to this sample. We chose an option for the same variance (homoscedastic case) as well as the varying variance (heteroscedastic case). The results of this test are summarized in Table 3. Key parameters from this test are the probability for a unimodal distribution ($p$), the ratio of the separation of the two peak colors relative to their widths ($D$), and the kurtosis $k$. If $D$ is larger than two, the distribution is...
considered to be bimodal. A negative value for $k$ is necessary for bimodal distributions.

In Table 3 the values of $p$ are close to zero ($<10^{-3}$), and the values of $D$ are larger than two for all cases. The values of $k$ are smaller than zero in all cases. Thus, these results show that the color distributions are indeed bimodal. The blue and red peaks are found to be at $(B - V) = 0.78 \pm 0.01$ and $0.99 \pm 0.02$, $(V - I) = 1.00 \pm 0.01$ and $1.20 \pm 0.01$ for the homoscedastic case, and at $(B - V) = 0.73 \pm 0.01$ and $0.93 \pm 0.03$, $(V - I) = 0.99 \pm 0.02$ and $1.18 \pm 0.02$ for the heteroscedastic case. In the case of the homoscedastic option, the number ratio of the blue GCs and the red GCs derived from the $(B - V)$ colors (200 versus 138) is similar to the value from the $(V - I)$ colors (201 versus 137). However, in the case of the heteroscedastic option, the number ratio of the blue GCs and the red GCs derived from the $(B - V)$ colors (107 versus 231) is significantly different from the value based on the $(V - I)$ colors (174 versus 164). Therefore, the results for the homoscedastic option appear to be more reliable.

In summary, we select, as the globular clusters, the compact and point sources ($C \leq 0.8$) with globular-cluster-like colors of $0.6 < (B - V) \leq 1.2$. For the following analysis, we divided the globular cluster sample into two subgroups according to their color: blue (metal-poor) globular clusters with $0.6 < (B - V) < 0.85$ and red (metal-rich) globular clusters with $0.85 < (B - V) < 1.2$. We chose, as the division colors, the colors with a minimum value between the two peaks in the color histograms.

Blue globular clusters in the brightest cluster galaxies (BCGs) often show a color–magnitude relation known as the blue tilt (see Harris et al. 2006, 2017 and references therein). In Figure 8, we display the $I - (B - I)$ CMD of the globular clusters in NGC 4589 to check the presence of any blue tilt. We divided the bright globular clusters with $21 < I < 24$ mag into five groups according to their $I$-band magnitudes in steps of $\Delta I = 0.5$ mag. We set the brightest magnitude bin to sample all the globular clusters with $21 < I < 22$ mag. The number of globular clusters in these groups ranges from 46 ($21 < I < 22$ mag) to 108 ($23.0 < I < 23.5$ mag).

We measured the mean colors of the blue and red globular clusters in each group using the GMM code. The measured values of $D$ were larger than two in all groups, but the values of $p$ were not always close to zero ($<10^{-3}$). This indicates that the unimodal distribution is not always rejected, although the bimodal distribution is meaningful in all cases. The same-variance and varying-variance options in the code yield similar colors for the faint bins ($I < 22.5$ mag), but slightly different values for the brighter bins ($I > 22.5$ mag). The difference in the brighter bins is due to the smaller sample size compared to that of the fainter bins.

Fitting the bright blue globular clusters with $21 < I < 23$ ($-11.1 < M_I < -9.1$) mag, we obtained the values of the slope $\gamma (21 < I < 23) = d(B - I)/dI = -0.034 \pm 0.036$ for the homoscedastic option and $\gamma (21 < I < 23) = -0.095 \pm 0.044$ for the heteroscedastic option. If we extend the magnitude range down to $I = 24$ ($M_I = -8.1$) mag, we obtain the slope values $\gamma (21 < I < 24) = -0.012 \pm 0.017$ and $-0.009 \pm 0.019$ for the homoscedastic and heteroscedastic options, respectively. Thus, the slope value for the bright globular cluster sample ($21 < I < 23$ mag) derived with the heteroscedastic option shows a hint of blue tilt at the level of $2\sigma$, while the values for the other cases do not.

Harris et al. (2006) presented an $M_I - (B - I)_0$ CMD for the combined sample of globular clusters in eight BCGs (their Figure 21), which shows clearly a blue tilt for $-11.8 < M_I < -9.5$ mag. They provided only a mass ($M$)–metallicity ($Z$) relation derived from the CMDs, $Z \propto M^{0.55}$, and did not present the value of the blue tilt slope in the CMD. We estimate the value of the slope for the blue tilt in their Figure 21, obtaining $\gamma \approx -0.9$. Thus the slope value for the bright globular cluster sample ($21 < I < 23$ mag) of NGC 4589 derived with the heteroscedastic option in this study, $\gamma = -0.095 \pm 0.044$, is similar to the mean slope for the BCGs in Harris et al. (2006). Recently, Harris et al. (2017) presented an $M_{F814W} - (F475W - F814W)_0$ CMD for the combined sample of globular clusters in five other BCGs (see their Figure 22), and they pointed out that the estimated slopes of the blue tilt show a large spread among galaxies, which range from $\gamma_M = d\log Z/d\log M \approx 0$ to $+0.27$ (or $\gamma = d\log F475W - F814W)/dF814W \approx 0$ to $-0.05$). These values are much smaller than that given in Harris et al. (2006), $\gamma_M = 0.55$.

### 3.4. Spatial Distributions of the Star Clusters

In Figure 9 we plotted the spatial distributions of the point and compact sources with $V < 25$ mag (left panels) and $25 < V < 27$ mag (right panels): (a) and (e) all sources, (b) and (f) blue sources ($(B - V) < 0.5$, bluer than the globular clusters), (c) and (g) blue globular clusters ($0.6 < (B - V) \leq 0.85$) and red globular clusters ($0.85 < (B - V) < 1.2$), and (d) and (h) red sources ($1.5 < (B - V) \leq 1.8$), redder than the

### Table 3

Summary of GMM Tests for Color Distributions of the GCs with $V < 25$ mag in NGC 4589

| Color | Blue GCs | | | Red GCs | | |
|-------|----------|---|---|----------|---|---|
|       | Mean     | $\sigma$ | $N_{\text{total}}$ | Mean | $\sigma$ | $N_{\text{total}}$ | $D^a$ | $p^b$ | $k^c$ |
| Homoscedastic$^{a,b}$ | $(B - V)$ | 0.78 ± 0.01 | 0.09 ± 0.01 | 200 ± 21 | 0.99 ± 0.02 | 0.09 ± 0.01 | 138 ± 21 | 2.38 ± 0.28 | 1.94e−4 | −0.493 |
|       | $(V - I)$ | 1.00 ± 0.01 | 0.08 ± 0.01 | 201 ± 14 | 1.20 ± 0.01 | 0.08 ± 0.01 | 137 ± 14 | 2.60 ± 0.20 | 3.93e−6 | −0.702 |
| Heteroscedastic$^c$ | $(B - V)$ | 0.73 ± 0.01 | 0.06 ± 0.02 | 107 ± 39 | 0.93 ± 0.03 | 0.12 ± 0.02 | 231 ± 39 | 2.06 ± 0.38 | 1.37e−5 | −0.493 |
|       | $(V - I)$ | 0.99 ± 0.02 | 0.07 ± 0.01 | 174 ± 33 | 1.18 ± 0.02 | 0.09 ± 0.01 | 164 ± 40 | 2.50 ± 0.24 | 2.94e−5 | −0.702 |

Notes.

$^a$ $D$ represents the ratio of the separation of the two peak colors relative to their widths, $p$ denotes the probability for a unimodal distribution, and $k$ is the kurtosis.

$^b$ Same variances for the Gaussian fits.

$^c$ Varying variances for the Gaussian fits.
globular clusters. In Figures 9(b) and (f), we also plotted the spatial distributions of the extended blue sources with $C > 0.8$ with solid circles in order to check their membership. The spatial distributions of these extended sources do not show any central concentration, which indicates that they are background galaxies. We also marked the positions of the galaxy center (cross) and SN 2005cz (yellow star) in the figure.

A few interesting features are noted in this figure. First, the spatial distributions of both blue and red globular clusters in Figures 9(c) and (g) show a strong central concentration around the galaxy center. This result implies that these sources are indeed globular clusters that are gravitationally bound to NGC 4589.

Second, the spatial distribution of the bright red sources (with $V \leq 25$ mag) in Figure 9(d) is roughly uniform, which
indicates that they are not the members of NGC 4589. Considering that the majority of these sources are point sources, we conclude that they are red dwarf stars in the Milky Way.

Third, the number-density contour maps in Figure 9(f) indicate that the spatial distribution of the faint blue sources appears to show a weak central concentration around the galaxy center. The nature of the faint blue sources will be checked further with their radial number density profile in the following section.

Fourth, the number-density contour map in Figure 9(h) indicates that the spatial distribution of the faint red sources appears to show a very weak central concentration around the galaxy center, but the number of sources is too small to be significant. In this figure, we plotted the red sources $1.5 < (B - V) < 1.8$ to avoid any contamination from the faint red globular clusters.

3.5. Radial Distributions of the Young Star Clusters

To further investigate the nature of the blue sources seen in the CMDs, we selected the blue sources with $C \leq 0.8$, $(B - V) \leq 0.5$, and $V \leq 27.0$ mag. The number of these blue sources is 46. Then we derived their radial number density profile, as plotted in Figure 10. The errors for the number density are Poisson errors.

In deriving the radial density profiles, we excluded the central region at $R < 0'1$, which masked out most of the dust lane. We also excluded out-of-the-edge/gap regions. We calculated the true area by counting individual “pixels,” which were used for the calculation of cluster properties. Pixels around saturated stars, background galaxies, and masked regions were not used. We corrected the incompleteness of our photometry using the completeness test results as a function of galactocentric distance.

The radial profile of the blue sources clearly shows a central excess at $R < 0'5$ ($\sim 3.8$ kpc) and a flattening at the level of $\Sigma \approx 3$ arcmin$^{-2}$ in the outer region at $R > 0'5$. This result shows that the blue sources in the central region at $R < 0'5$ are mainly the members of NGC 4589, while those in the outer region at $R > 0'5$ are most likely background galaxies. Considering as well that they are mostly compact (slightly resolved) sources, we conclude that the blue sources in the central region are mainly genuine young star clusters in this galaxy.

We estimate the background level for the blue sources using the region at $R > 1'$, and we obtain $\Sigma = 3.0 \pm 1.3$ arcmin$^{-2}$. Subtracting the background level, we derive the total number of young star clusters with $24.5 < V < 27$ at $R < 0'5$ and obtain $N_{YSC} = 16 \pm 6$. From the comparison of these sources with the SSP models for solar metallicity and $Z > 0.1 Z_{\odot}$ (Girardi et al. 2000) as shown in Figure 5, we estimate their ages to be 10 Myr to 1 Gyr and their stellar masses to be $M = 10^{-3}$ to $10^{4.5} M_{\odot}$. These values change little even if we use the SSP models for $Z > 0.1 Z_{\odot}$.

3.6. Radial Distributions of the Globular Clusters

We derived the radial number density profiles of the bright globular clusters with $V \leq 25$ mag in NGC 4589: all globular clusters, the blue globular clusters, and the red globular clusters. We corrected the radial profiles for the incompleteness using the results from the artificial source test.

Since the HST field is not large enough to cover the background region, it is difficult to estimate the background level. Therefore, we present the results without background
correction. The results for the outer region at $R > 2'$ are uncertain. Figure 11(a) displays the radial number density profiles of these globular clusters.

Fitting the profiles for $R \leq 2.5$ with a Sérsic law (Sérsic 1963), we obtain the Sérsic index values, $n_{\text{AGC}} = 1.41 \pm 0.34$ for all globular clusters, $n_{\text{BGC}} = 1.07 \pm 0.28$ for the blue globular clusters, and $n_{\text{RGC}} = 1.89 \pm 0.83$ for the red globular clusters. These values are similar to those of NGC 4921 (Lee & Jang 2016). The corresponding effective radii of the globular cluster systems are $R_{\text{eff,AGC}} = 0.94 \pm 0.09$, $R_{\text{eff,BGC}} = 0.90 \pm 0.08$, and $R_{\text{eff,RGC}} = 1.00 \pm 0.22$, respectively. Although the Sérsic index value for the blue globular clusters is slightly smaller than that for the red globular clusters, the difference is within errors. In most massive galaxies, the blue globular clusters have a shallower density profile than the red globular clusters (Lee et al. 1998; Brodie & Strader 2006, and references therein; see also Cho et al. 2016; Lee & Jang 2016; Harris et al. 2017). Therefore, NGC 4589 is a rare example that shows both blue and red subpopulations that have similar radial profiles.

For comparison, we also plotted the $V$-band radial surface-brightness profile, $\mu_V$, of the galaxy light derived from the F555W image using the IRAF/ellipse task. We estimated the background levels using the area at $R > 2.5$ and used them for background subtraction.

We converted the unit for the surface brightness profile of the galaxy light, the magnitude per square arcsec, into log(flux per square arcmin). In the figure we plotted $\mu_V/2.5$ for direct comparison with the radial number density profiles of globular clusters. We shifted the resulting radial profile of the galaxy light along the vertical direction to match the radial number density profile of the blue and red globular clusters at $R \approx 0.7$.

In the right vertical axis we labeled the scale for the surface brightness profile.

Sérsic law fitting for the galaxy light with $0.1 < R < 2.0$ gives a Sérsic index of $n_{\text{galaxy}} = 3.11 \pm 0.21$ (with $R_{\text{eff,galaxy light}} = 0.47 \pm 0.01$), showing that the galaxy light follows the de Vaucouleurs law. The radial profile of all globular clusters is flatter than the surface brightness profile of the galaxy light, and the effective radius of the entire globular cluster system ($R_{\text{eff,AGC}} = 0.94 \pm 0.09$) is two times larger than the value for the galaxy light ($R_{\text{eff,galaxy light}} = 0.47 \pm 0.01$). This shows that the globular cluster system is more extended than the galaxy light, which is also seen in many other galaxies (see Brodie & Strader 2006 and references therein).

In Figure 11(b) we plot the radial variation of the $(B - V)$ color of the galaxy light. The color of the galaxy light is redder than $(B - V) = 1.0$ in the central region at $R \leq 0.1$ and becomes slowly bluer from $(B - V) = 1.0$ at $R = 0.1$ to $(B - V) = 0.8$ at $R = 1.2$. As shown in the color–color diagram (Figure 6), SSP models show that an old stellar population with $-2.3 < [\text{Fe/H}] < +0.2$ can have $(B - V)$ colors ranging from 0.6 to 1.1 mag. Thus, the integrated color of the galaxy light is consistent with colors of the old stellar populations with a large range of metallicities.

### 3.7. Luminosity Functions of the Globular Clusters

We derived $V$-band and $I$-band GCLFs for NGC 4589 by counting the number of globular clusters at $0.2 < R < 2.0$. We excluded the central region at $R < 0.2$, where the completeness is much lower than the outer region. We corrected the GCLFs for the completeness using the results of the completeness test. In Figure 12 we display $V$- and $I$-band GCLFs: for all globular clusters (top panels), the blue globular clusters (middle panels), and the red globular clusters (bottom panels). The GCLFs in the figure appear to be approximately

![Figure 12](image-url)
Gaussian, showing a turnover (peak) at $V \approx 24.5$ mag ($I \approx 23.5$ mag).

We fit the GCLFs with a Gaussian function for the magnitude range $V \leq 26.0$ mag ($I \leq 25.0$ mag), where incompleteness of our photometry is not significant. We obtain the values of the turnover magnitudes and widths as summarized in Table 4. The turnover magnitudes and widths for all globular clusters are $V(\text{max}) = 24.53 \pm 0.06$ mag with $\sigma = 0.96 \pm 0.05$ and $I(\text{max}) = 23.47 \pm 0.07$ mag with $\sigma = 1.03 \pm 0.07$.

It is noted that the widths of the GCLFs for NGC 4589 are smaller than the value for Milky Way globular clusters, $\sigma = 1.2$–1.4 for the $V$ band (Di Criscienzo et al. 2006; Rejkuba 2012), and those for other elliptical galaxies, $\sigma \approx 1.3$, in Kundu & Whitmore (2001). Kundu & Whitmore (2001) could not determine the value of the width for NGC 4589 because of the shallow photometric limit. However, the values in this study are similar to those for NGC 4921, the brightest spiral galaxy in Coma, $\sigma = 1.0$–1.1 for the $V$ and $I$ bands based on deep HST images (Lee & Jang 2016). We note that the data in this study go much deeper than that in Kundu & Whitmore (2001) and that the size of the globular cluster sample in NGC 4589 is much larger than the size of the Milky Way globular cluster sample.

Jordán et al. (2007) derived a relation between the $g$- and $z$-band GCLF width and the absolute $B$-band magnitude of their host galaxies from the ACSVCs sample: $\sigma_g = (1.14 \pm 0.01) - (0.100 \pm 0.007) (M_B,\text{gal} + 20)$ (similar results, but for $M_{\text{galfc}}$, were given later for the combined sample of ACSVCs and ACSFSCs by Villegas et al. 2010). If we use this relation for the luminosity of NGC 4589 ($M_B = -20.47 \pm 0.23$ mag), we obtain a value of $\sigma_g = 1.19$. The scatter of this relation for the magnitude range of NGC 4589 in Figure 9 of Jordán et al. (2007) is estimated to be about $\pm 0.1$. Thus the GCLF width of NGC 4589 in this study is $\sim 0.2$ smaller than the value expected from Jordán et al. (2007) at the level of $2\sigma$.

The $V$-band turnover magnitude for the blue globular clusters ($V(\text{max}) = 24.48 \pm 0.09$ mag) is $0.10$ mag brighter than that for the red globular clusters ($V(\text{max}) = 24.58 \pm 0.10$ mag). However, this difference is at the level of $1\sigma$, so it is not significant. On the other hand, the $I$-band turnover magnitude for the blue globular clusters ($I(\text{max}) = 23.45 \pm 0.07$ mag) is nearly the same as the value for the red globular clusters ($I(\text{max}) = 23.50 \pm 0.12$ mag). The widths for the blue globular clusters and the red globular clusters are found to be similar.

### 3.8. Total Number and Specific Frequency of Globular Clusters

We estimate the total number of globular clusters in NGC 4589 using the radial number density profile and luminosity function of the globular clusters and keeping the area coverage of the HST/ACS field in mind. We counted the number of blue and red globular clusters brighter than $V = 25$ mag in $R \leq 0.94 \pm 0.09$, which is the half number radius of all globular clusters we measured from the radial number density profile. It is not easy to estimate the foreground or background contamination in this value when considering the limit of the HST field. However, the globular cluster density is moderately high inside the half number radius of the globular cluster system, so the contribution of the foreground or background sources must not be significant. Assuming a Gaussian luminosity distribution of the globular clusters with a peak at $V = 24.53 \pm 0.06$ mag and a width of $0.96 \pm 0.05$, we obtain the total number of globular clusters in NGC 4589 to be $N$ (total) $= 640 \pm 50$. The error is derived from individual measurement errors associated with the half number radius and the luminosity distribution of the globular clusters. From this number and the absolute magnitude of NGC 4589 ($M_V = -21.41 \pm 0.23$ mag), we estimate the specific frequency and obtain $S_N = 1.7 \pm 0.2$. This value is similar to the mean value for bright E galaxies with luminosities similar to that of NGC 4589 (Harris et al. 2013).

### 3.9. GCLF Turnover Magnitude Calibration

We estimate the distance to NGC 4589 using the GCLF method as applied to the case of Coma galaxies in Lee & Jang (2016). The turnover magnitude of the GCLFs has been used as a standard candle for a long time (Harris 2001; Richtler 2003; Di Criscienzo et al. 2006; Rejkuba 2012). It is known that the $V$-band turnover magnitudes of the metal-poor globular clusters are brighter than or equal to those of the metal-rich globular clusters, and that this magnitude difference between the two subpopulations shows a large spread among galaxy samples (Di Criscienzo et al. 2006; Rejkuba 2012). In an extensive review of the GCLF method, Rejkuba (2012) concluded that the luminosity functions of the metal-poor (blue) globular clusters are a better distance indicator than those using the entire sample of globular clusters because they show smaller scatter and because they are independent of the fraction of metal-rich globular clusters, which varies depending on the galaxy. Therefore we use the luminosity functions of the blue globular clusters to estimate the distance to NGC 4589.

We adopt the calibration of the $V$-band turnover magnitudes for the metal-poor globular clusters given by Di Criscienzo et al. (2006). For the zero-point calibration of the $H_0(\text{RR})$–[Fe/H] relation to be used for distance estimation of the globular clusters, Di Criscienzo et al. (2006) adopted a distance to the LMC, $(m - M)_0 = 18.50$. This value is close to the recent geometric measurement based on eclipsing binaries of the LMC (Pietrzyński et al. 2013), $(m - M)_0 = 18.494 \pm 0.008(\text{ran}) \pm 0.008(\text{sys})$.

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**Table 4**

Summary of Gaussian Fits for LFs of All GCs, Blue GCs, and Red GCs in NGC 4589

|        | Center | Width | $N_{\text{total}}$ |
|--------|--------|-------|------------------|
| **V**  |        |       |                  |
| All GCs, 0.2 < $R < 2'$ | 24.53 ± 0.06 | 0.96 ± 0.05 | 472 ± 25 |
| Blue GCs | 24.48 ± 0.09 | 0.96 ± 0.07 | 230 ± 17 |
| Red GCs  | 24.58 ± 0.10 | 1.05 ± 0.10 | 242 ± 19 |
| **I**  |        |       |                  |
| All GCs, 0.2 < $R < 2'$ | 23.47 ± 0.07 | 1.03 ± 0.07 | 478 ± 26 |
| Blue GCs | 23.45 ± 0.07 | 0.86 ± 0.06 | 218 ± 16 |
| Red GCs  | 23.50 ± 0.12 | 1.14 ± 0.12 | 243 ± 21 |

**Note.**

$^a$ The errors for the numbers are from the fitting errors for the integration of Gaussian functions provided by IDL/mpfitexpr.
Summary of GCLF Distance Estimation for NGC 4589

| Parameter                                    | Value               | Remarks                      |
|----------------------------------------------|---------------------|------------------------------|
| Systematic errors of the GCLF method         |                     |                              |
| $M_V$ (max) (metal-poor GC)                  | $-7.66 \pm 0.09^a$  | Di Criscienzo et al. (2006)  |
| Zero-point error of $M_V$–[Fe/H](RR) relation| $\pm0.05^b$         | Di Criscienzo et al. (2006)  |
| Adopted error for metal-poor GC calibration of $M_V$ (max) | $\pm0.10^c$ | This study                  |
| Intrinsic uncertainty of the turnover magnitudes (metal-poor GC) | $\pm0.14^d$ | This study                  |
| Total systematic error of the GCLF method based on metal-poor GCs | $\pm0.14^d$ | This study                  |

NGC 4589

| Foreground extinction, $A_V$                  | $0.077 \pm 0.04$    | Schlafly & Finkbeiner (2011) |
| $V$(max) (blue GC)                            | $24.48 \pm 0.09$   | This study                   |
| $V$(max)$_0$ (blue GC)                        | $24.40 \pm 0.10$   | after extinction correction |
| Aperture correction error                     | $\pm0.03$          | This study                   |
| Transformation error                          | $\pm0.03$          | Sirianni et al. (2005)       |
| Total systematic error of the distance modulus| $\pm0.15^e$        | This study                   |
| Distance modulus, $(m - M)_0$                 | $32.06 \pm 0.18$   | $\pm0.10$ (ran) $\pm 0.15$(sys) |
| Distance, $d$ [Mpc]                           | $25.8 \pm 2.2$     | $\pm1.2$ (ran) $\pm 1.8$(sys) |

Notes.

- $^a$ Based on the samples of the metal-poor globular clusters in the Milky Way, M31, and 14 early-type galaxies (Di Criscienzo et al. 2006). The error denotes the mean error of the GCLF turnover magnitudes for the three samples of calibrator galaxies.
- $^b$ The error of the zero point for the $M_V$(RR)–[Fe/H] relations used in Di Criscienzo et al. (2006).
- $^c$ The sum of the mean calibration error and the error for the $M_V$(RR)–[Fe/H] relations.
- $^d$ Note that the intrinsic uncertainty of the turnover magnitudes based on the entire globular clusters is $\pm0.2$ mag (Richter 2003; Rejkuba 2012).
- $^e$ The sum of the calibration error of $M_V$(max) and intrinsic uncertainty of the turnover magnitudes of the metal-poor globular clusters.
- $^f$ The sum of the aperture correction and transformation errors for NGC 4589 and the total systematic error of the GCLF method based on metal-poor globular clusters.

0.048(sys). A better calibration of the GCLF with updated data for the GCLF and the distance to their host galaxies is needed in the future. Di Criscienzo et al. (2006) derived a calibration from the selected sample of 74 metal-poor ([Fe/H] < −1.0) globular clusters located in the outer region at $2 < R_{GC} < 35$ kpc with relatively lower reddening values with $E(B - V) < 1.0$ in the Milky Way. In the Milky Way, we can observe globular clusters that are even located close to the galaxy center in addition to the halo globular clusters, but we can only observe mostly halo globular clusters in other galaxies. Therefore, the sample of globular clusters we observe in other galaxies is mostly made up of halo globular clusters, and it is closer to the sample of MW halo globular clusters, rather than to the entire sample of MW globular clusters. From this sample, Di Criscienzo et al. (2006) obtained $M_{V, MWG}$ (max) = −7.66 ± 0.11 mag. Then they derived similar calibrations from the samples of the metal-poor globular clusters in M31 and a set of 14 early-type galaxies in the literature: $M_{V, M31}$ (max) = −7.65 ± 0.19 mag and $M_{V, ETG}$ (max) = −7.67 ± 0.23 mag. These three values are in excellent agreement, but they are derived from galaxies with a wide range of morphological types, luminosity, and mass. Di Criscienzo et al. (2006) suggested, as a final calibration for the metal-poor globular clusters, a weighted mean of these three values, $M_V$ (max) = −7.66 ± 0.09 mag.

The error of the zero point for the $M_V$(RR)–[Fe/H] relations adopted for the calibration of the turnover magnitudes in Di Criscienzo et al. (2006) is ±0.05 mag. Combining this zero-point error and the mean error of the $M_V$ (max) calibration, we estimate the systematic error for the metal-poor globular cluster calibration of $M_V$ (max) to be ±0.10 mag.

There is another source for the systematic error of the GCLF method, which is an intrinsic uncertainty (scatter) of the turnover magnitudes of the GCLFs. In the review of the GCLF method, Rejkuba (2012; M. Rejkuba 2018, private communication) discussed several factors for the errors of the GCLF methods that use the entire globular cluster sample in a galaxy, which include environmental effects, dependence on the properties of their host galaxies, and metallicity difference between the calibrator sample and the target sample. She suggested that the turnover magnitudes of the GCLF vary from galaxy to galaxy at the level of ±0.2 mag because the intrinsic dispersion of the turnover magnitudes depends on the sampled globular cluster system in a galaxy. Therefore, the systematic error for galaxy-to-galaxy GCLF turnover magnitude scatter due to population and sampling effects is estimated to be ±0.2 mag in the case of the turnover magnitude measurements based on the entire globular clusters in a galaxy.

If we use only the metal-poor globular clusters, the corresponding uncertainty will be much smaller than the error based on the entire globular cluster samples because the metal-poor globular cluster calibrations based on three different samples of galaxies in Di Criscienzo et al. (2006) agree at the level of 0.01 mag. It is difficult to estimate a precise value of this error at the moment. In this study we adopt the error, in a conservative manner, to be ±0.1 mag.

Combining this error due to the intrinsic scatter (±0.1) and the systematic error of the $M_V$(max) calibration (±0.10), we estimate the total systematic error for the GCLF distance estimation to be ±0.14 mag in the case of the metal-poor globular cluster samples. The corresponding error will be ±0.22 mag in the case of the entire globular cluster samples. We summarize these errors in Table 5.

3.10. GCLF Distance Estimation for NGC 4589

Applying the adopted $V$-band calibration for the metal-poor globular clusters ($M_V$(max) = −7.66 ± 0.14) to the measured
turnover magnitude \((V_{\text{max}}) = 24.48 \pm 0.09\) and \(V(\text{max})_{0} = 24.40 \pm 0.10\), we derive the distance to NGC 4589: \((m - M)_{0} = 32.06 \pm 0.10(\text{ran}) \pm 0.15(\text{sys}) = 32.06 \pm 0.18 \ (d = 25.8 \pm 2.2 \text{ Mpc})\). For the calculation of the errors, we included all uncertainties due to foreground extinction correction, aperture correction, and transformation uncertainties, as summarized in Table 5.

4. Discussion

4.1. The Origin of SN 2005cz and Ca-rich SNe Ib

To explain the spectral features and the light curves of SN 2005cz, Kawabata et al. (2010) suggested that the origin of SN 2005cz is a core-collapse supernova whose progenitor is a massive star at the low-mass end \((8–12 \ M_{\odot})\) in a binary system. They noted a possible relation between SN 2005cz and the nucleus composed of young stars in the nucleus. The progenitor of SN 2005cz might have come from these young stars in the nucleus.

Later, Suh et al. (2011) presented, from GALEX NUV and SDSS photometry, that the observed \((\text{NUV} - r)\) color of NGC 4589 is close to the color of a galaxy that had little recent star formation (see their Figure 2). Considering the possible presence of internal extinction due to dust clouds, they inferred that the intrinsic color of NGC 4589 may be much bluer than the observed color, and they favored the massive-star origin of SN 2005cz. They suggested that the progenitor of SN 2005cz may have a mass of \(5–6 \ M_{\odot}\), which is even lower than the value of \(8–12 \ M_{\odot}\) suggested by Kawabata et al. (2010). However, there is no information on the estimated value of the internal extinction, so it is not possible to tell whether the observed color is intrinsically red or significantly reddened by internal dust.

In contrast, Perets et al. (2011) used optical spectroscopy, \(H_{0}\) emission, GALEX UV emission, and \(HST\) images to search for any signatures of young stellar populations around SN 2005cz. In particular, they tried to find young, massive stars \((M > 15 \ M_{\odot})\) from the photometry of point sources around the SN location using \(HST\)/WFPC2 and ACS images. However, Perets et al. (2011) found no feature of any young stellar population either close to or far \((>1.5 \text{kpc})\) from the position of SN 2005cz, supporting the old, low-mass star origin scenario of SN 2005cz. Perets et al. (2011) disfavored the massive-star origin of SN 2005cz and showed that the SED of NGC 4589 covering GALEX FUV to 2MASS \(K_s\) is fitted very well by an old galaxy model with an age of 12.5 Gyr, stellar mass of \(10^{11.5} \ M_{\odot}\), and no specific star formation rate.

In this study, we found a small population of young star clusters in the central region at \(R < 0.5 \ (<3.8 \text{kpc})\) that includes the location of SN 2005cz. Most of these star clusters are slightly resolved (i.e., larger than point sources), so they cannot be individual stars in NGC 4589. Their colors range from \((B - V) = 0\) to \(0.5 \ (<V - I = 0.2\) to 0.7\), which indicates that they are younger than about \(10^4\) yr. The magnitudes of these clusters are \(25 < V \leq 27\) \((-7.1 < M_V \leq -5.1\) \(\text{mag}\). These magnitudes correspond to the masses of \(10^{3.8} - 10^{4.9} \ M_{\odot}\) for the Padova SSP models with solar metallicity. The mass range does not change much with the choice of metallicity for \(Z \geq 0.1 \ Z_{\odot}\). These young clusters are found only in the central region at \(R < 0.5\) \(<3.8 \text{kpc}\), while old globular clusters are found in a much wider area with a much higher abundance. These young star clusters might have formed in relation with a recent merger that resulted in a rotating dust disk (Moellenhoff & Bender 1989). They might have provided a massive-star progenitor for SN 2005cz. Therefore, our finding of young star clusters in the central region of NGC 4589 supports the massive-star progenitor scenario for the origin of Ca-rich SNe Ib.

4.2. Comparison with the Previous GCLF

Using shallow \(HST\)/WFPC2 \(F555W\) and \(F814W\) images, Kundu & Whitmore (2001) derived a GCLF for NGC 4589 from the sample of globular clusters with \(21 < V < 24.5\) \(\text{mag}\). They could not determine the value of the GCLF width for NGC 4589 because of the shallow photometric limit. They fitted it with a Gaussian function for a fixed width of \(\sigma = 1.3\). They obtained turnover magnitudes of \(V(\text{max})_{0} = 25.22 \pm 0.39\) and \(R(\text{max})_{0} = 24.21 \pm 0.41\). These values are \(\sim0.8\) \(\text{mag}\) fainter than those in this study, \(V(\text{max})_{0} = 24.45 \pm 0.07\) \(\text{mag}\) and \(R(\text{max})_{0} = 23.43 \pm 0.07\) \(\text{mag}\). The turnover magnitudes in Kundu & Whitmore (2001) are about 0.9 \(\text{mag}\) fainter than the 50\% completeness limits of their photometry, \(V_{\text{lim}} = 24.3\) \(\text{mag}\) and \(R_{\text{lim}} = 23.2\) \(\text{mag}\). Their photometry did not reach the turnover magnitudes, and the errors of their estimated magnitudes are as large as 0.4 \(\text{mag}\). Note that our photometry reaches much deeper than the turnover magnitudes. Therefore, the differences between Kundu & Whitmore (2001) and this study are considered to be mainly due to the shallow photometry in Kundu & Whitmore (2001).

Kundu & Whitmore (2001) also presented the total number of globular clusters, \(N(\text{total}) = 789 \pm 123\), and the specific frequency, \(S_N = 5.1 \pm 3.7\). In this estimation, they adopted \((m - M)_{0} = 31.95\) and \(M_V = -21.2\) \(\text{mag}\) for NGC 4589. However, this value is a local \(S_N\), constructed from a shallow photometry of a sample based on only a small fraction of the entire galaxy, so it cannot be compared directly with our estimate.

4.3. Comparison with Previous Distance Estimates

In Table 6, we list the previous estimates of the distance to NGC 4589 based on various methods. The distances based on the \(D_{\sigma-\sigma}\) relation, the Faber–Jackson relation, and the Tully–Fisher relation show a large scatter \((m - M)_{0} = 31.60\) to 33.91 and have large errors from 0.25 to 0.40 \(\text{mag}\) (de Vaucouleurs & Olson 1984; Faber et al. 1989; Willick et al. 1997; Theureau et al. 2007). The distance in this study, \((m - M)_{0} = 32.06 \pm 0.18 \ (d = 25.8 \pm 2.2 \text{ Mpc})\), is in the middle of these values.

In contrast, the distances based on the SBF have smaller errors than the others. Tonry et al. (2001) presented a distance of \((m - M)_{0} = 31.71 \pm 0.22\) based on the I-band SBF. This value was updated to a 0.16 \(\text{mag}\) smaller value later by Jensen et al. (2003), \((m - M)_{0} = 31.55 \pm 0.22\), who used the Udalski.
et al. (1999) Cepheid period–luminosity relation for the calibration of the method. However, metallicity correction for Cepheid distances needs to be taken into account for better distance estimation. Considering this, Blakeslee et al. (2010) published a correction formula to Tonry et al. (2001) distances (see Appendix A of the paper). The appendix also contains some clarifications on the differences between the SBF distances by Tonry et al. (2001) and by Jensen et al. (2003). According to this correction, the revised distance modulus to NGC 4589 is derived to be $m - M_0 = 31.77 \pm 0.22$ mag.

Jensen et al. (2003) also presented near-IR SBF measurements of NGC 4589. The distance modulus to NGC 4589 based on the near-IR SBF measurements can be derived using the $\bar{m}_{F160W}$ value in their Table 2 (column 4) and the $\bar{M}_{F160W}$ value in their Equation (1). We derive a distance modulus $(m - M_0) = 27.21(\pm0.08) + 4.76(\pm0.03) = 31.97 \pm 0.09$ mag. Following the suggestion in Blakeslee et al. (2010), we apply the correction for the metallicity-dependent Cepheid zero point of Tonry et al. (2001), 0.1 mag, to this value, and we obtain $(m - M_0) = 32.07 \pm 0.09$.

All of the errors in the above SBF distances are random errors. The systematic error of each of the optical and near-IR SBF distances is $\sim\pm0.1$ mag based on the Cepheid zero-point error (Jensen et al. 2003; Cantiello et al. 2018). Considering both the random errors and the systematic errors, the distance moduli based on optical and near-IR SBF measurements to NGC 4589 are $(m - M_0)_{\text{optical SBF}} = 31.77 \pm 0.24$ and $(m - M_0)_{\text{near-IR SBF}} = 32.07 \pm 0.13$, respectively.

Thus, the near-IR SBF distance modulus is 0.3 $\pm$ 0.3 mag larger than the optical SBF value. However, the difference is similar to its error, so both values agree at the level of $1 \sigma$. The distance in this study, $(m - M_0) = 32.06 \pm 0.18$, is 0.3 mag larger than the revised optical SBF distance, $(m - M_0) = 31.77 \pm 0.24$, but is in excellent agreement with the near-IR SBF distance, $(m - M_0) = 32.07 \pm 0.13$ (Jensen et al. 2003; Blakeslee et al. 2010).

5. Summary and Conclusion

Using deep HST/ACS images, we detected a significant population of star clusters in NGC 4589. This population is dominated by old globular clusters, but includes a small population of young star clusters in the central region. We present $BV$ photometry of these clusters in the Vega magnitude system. The main results are summarized as follows:

1. We found a small population of young star clusters with age $<10^5$ yr in the central region at $R < 0.5$ (<3.8 kpc) of NGC 4589. These young clusters might have provided a massive-star progenitor for SN 2005cz, which supports the massive-star origin scenario of Ca-rich SNe Ib.

2. The color distribution of the globular clusters is clearly bimodal. GMM analysis with a homoscedastic option identifies a blue peak at $(B - V) = 0.78 \pm 0.01 ((V - I) = 1.00 \pm 0.01)$ and a red peak at $(B - V) = 0.99 \pm 0.02 ((V - I) = 1.20 \pm 0.01)$. With a heteroscedastic option, we find the blue and red peaks at similar colors: $(B - V) = 0.73 \pm 0.01 ((V - I) = 0.99 \pm 0.02)$ and $(B - V) = 0.93 \pm 0.03 ((V - I) = 1.18 \pm 0.02)$.

3. The radial number density profile of the globular clusters is flatter than the surface brightness profile of the stellar light. The former is fitted by a Sérsic law with $n_{\text{AGC}} = 1.41 \pm 0.34$, while the latter is fitted well by a Sérsic law with $n_{\text{galaxy}} = 3.11 \pm 0.21$, which is close to the de Vaucouleurs profile.

4. The GCLFs are fitted well by a Gaussian function. The $V$-band turnover magnitudes for all globular clusters, the blue globular clusters, and the red globular clusters are found to be similar: $V_{\text{AGC(GC,max)}} = 24.53 \pm 0.06$ mag for all globular clusters, $V_{\text{BGCG(max)}} = 24.48 \pm 0.09$ mag for the blue globular clusters, and $V_{\text{RGC(max)}} = 24.58 \pm 0.10$ mag for the red globular clusters. The corresponding $V$-band widths are also found to be similar: $\sigma_{\text{AGC}} = 0.96 \pm 0.05$, $\sigma_{\text{BGCG}} = 0.96 \pm 0.07$, and $\sigma_{\text{RGC}} = 1.05 \pm 0.10$.

5. We derived the total number of globular clusters to be $N$ (total) = 640 $\pm$ 50 and the specific frequency to be $S_N = 1.7 \pm 0.2$.

6. Considering the calibration errors of the turnover magnitudes ($\pm0.1$ mag) and the intrinsic variation depending on their host galaxies and environment ($\pm0.1$ mag), we estimate the total systematic error for the GCLF distance measurement to be $\pm0.14$ mag in the case of the metal-poor globular cluster sample, and $\pm0.22$ mag in the case of the entire globular cluster sample.

7. Adopting the calibration for the metal-poor globular clusters (Di Criscienzo et al. 2006; Rejkuba 2012), we derive a distance to NGC 4589 from the turnover magnitude of the blue globular clusters: $(m - M_0) = 32.06 \pm 0.18$ and $d = 25.8 \pm 2.2$ Mpc. The distance
modulus in this study is in excellent agreement with the near-IR SBF distance, \((m - M)_0 = 32.07 \pm 0.13\), but 0.3 mag larger than the revised optical SBF distance, \((m - M)_0 = 31.77 \pm 0.24\) (Jensen et al. 2003; Blakeslee et al. 2010).

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