Ages and structural and dynamical parameters of two globular clusters in the M81 group

Jun Ma,1,2 Song Wang,1,2 Zhenyu Wu,1,2 TianMeng Zhang,1,2 Hu Zou,1 Zhimin Zhou,1 Jundan Nie,1 Xu Zhou,1 Xiyang Peng,1 Jiali Wang,1 Jianghua Wu,3 Cuihua Du4 and Qirong Yuan5

1 Key Laboratory of Optical Astronomy, National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China
2 College of Astronomy and Space Sciences, University of Chinese Academy of Sciences, Beijing 100049, China
3 Department of Astronomy, Beijing Normal University, Beijing 100875, China
4 School of Physics Sciences, University of the Chinese Academy of Sciences, Beijing 100049, China
5 Department of Physics, Nanjing Normal University, WenYuan Road 1, Nanjing 210046, China

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ABSTRACT

GC-1 and GC-2 are two globular clusters (GCs) in the remote halo of M81 and M82 in the M81 group discovered by Jang et al. using the Hubble Space Telescope (HST) images. These two GCs were observed as part of the Beijing–Arizona–Taiwan–Connecticut (BATC) Multicolor Sky Survey using 14 intermediate-band filters covering a wavelength range of 4000–10 000 Å. We accurately determine these two clusters’ ages and masses by comparing their spectral energy distributions (from 2267 to 20 000 Å, comprising photometric data in the near-ultraviolet of the Galaxy Evolution Explorer, 14 BATC intermediate-band and Two Micron All Sky Survey near-infrared JHKs filters) with theoretical stellar population-synthesis models, resulting in ages of 15.50 ± 3.20 Gyr for GC-1 and 15.10 ± 2.70 Gyr for GC-2. The masses of GC-1 and GC-2 obtained here are 1.77–2.04 × 10^6 and 5.20–7.11 × 10^6 M⊙, respectively. In addition, the deep observations with the Advanced Camera for Surveys and Wide Field Camera 3 on the HST are used to provide the surface brightness profiles of GC-1 and GC-2. The structural and dynamical parameters are derived from fitting the profiles to three different models; in particular, the internal velocity dispersions of GC-1 and GC-2 are derived, which can be compared with ones obtained based on spectral observations in the future. For the first time, in this paper, the r_h versus M_V diagram shows that GC-2 is an ultra-compact dwarf in the M81 group.

Key words: galaxies: evolution – galaxies: star clusters: general – galaxies: star clusters: individual: M81 – galaxies: star clusters: individual: M82.

1 INTRODUCTION

The study of globular clusters (GCs) plays an important role in our understanding of the evolution and history of galaxies. The Galactic GCs, the stars of which are thought to be among the oldest objects in the universe, can provide important information regarding the minimum age of the universe and the early formation history of our Galaxy. In addition, studying the spatial structures and dynamics of GCs is of great importance for understanding both their formation conditions and dynamical evolution within the tidal fields of their galaxies (Barmby et al. 2007).

The most direct method to determine a cluster’s age is by employing main-sequence photometry, since the absolute magnitude of the main-sequence turn-off is predominantly affected by age (see Puzia et al. 2002, and references therein). However, this method was mainly applied to the star clusters in the Milky Way and its satellites (e.g. Rich, Shara & Zurek 2001). Generally, the ages of extragalactic star clusters are determined by comparing their observed spectral energy distributions (SEDs) and/or spectroscopy with the predictions of simple stellar population (SSP) models (see Ma et al. 2010, and references therein).

The structural and dynamical parameters of clusters are often determined by fitting the surface brightness profiles to a number of different models, combined with mass-to-light ratios (M/L values) estimated from velocity dispersions or population-synthesis models. We only mention three models that will be used in this paper. The first is based on a single-mass, isotropic, modified isothermal sphere...
developed by King (1966). The second is a further modification of a single-mass, isotropic isothermal sphere based on the ad hoc stellar distribution function of Wilson (1975). The third model is based on the $R^{1/n}$ surface density profile of Sérsic (1968). Using the three models, some authors have achieved some success in determining structural and dynamical parameters of clusters in the Local galaxies: the Milky Way, the Large and Small Magellanic Clouds, Fornax and Sagittarius dwarf spheroidal galaxies (Mclaughlin & van der Marel 2005), M31 (Barmby et al. 2007, 2009; Wang & Ma 2013), NGC 5128 (Mclaughlin et al. 2008) and M33 (Ma 2015).

Except for the Local Group galaxies, the M81 group includes the nearest large spirals outside the Local Group. M81 locates in the centre of the M81 group, and 36 member galaxies surround M81 (Chiboucas et al. 2013). Although the GC system of M81 has come under recent detailed scrutiny (see Ma et al. 2013, and references therein), however structural and dynamical studies of the GC system of the M81 group are very limited: Chandar, Ford & Tsvetanov (2001) estimated the core radii of 114 compact star clusters of M81 based on the Hubble Space Telescope (HST)/Wide Field Planetary Camera 2 imaging; Nantais et al. (2011) estimated the effective radii of 419 GC candidates of M81 using HST/Advanced Camera for Surveys (ACS) imaging; and Lim, Hwang & Lee (2013) estimated the effective radii of 1105 star clusters in M82 using HST/ACS imaging. Jang et al. (2012) and Mayya et al. (2013) determined structural parameters for three GCs in the M81 group by fitting the King models to the surface brightness profiles of the HST images. However, for two of them (i.e. GC-1 and GC-2), Jang et al. (2012) only derived their core and half-light radii. GC-1 and GC-2 are of interest because they are in the remote haloes of M81 and M82 in the M81 group recently discovered by Jang et al. (2012); in particular, GC-2 is the most isolated GC in the local universe. So, we will derive the structural and dynamical parameters of GC-1 and GC-2. In addition, we will also accurately determine these two clusters’ ages and masses by comparing their SEDs with theoretical stellar population-synthesis models.

The distances were taken to be $(m-M)_0 = 27.80 \pm 0.03$ to GC-1 and $(m-M)_0 = 28.04 \pm 0.04$ to GC-2 throughout, which were derived by Jang et al. (2012).

In this paper, we will determine the ages and masses, and structural and dynamical parameters, for GC-1 and GC-2. We will describe the details of the observations and our approach to the data reduction with the Beijing–Arizona–Taiwan–Connecticut (BATC) system in Section 2, and with the HST programs in Sections 2 and 4. We will determine the ages and masses of GC-1 and GC-2 by comparing observational SEDs with population-synthesis models in Section 3, and determine structural and dynamical parameters of GC-1 and GC-2 in Section 5. We make comparison to previous results and discussion in Section 6, and provide a summary in Section 7.

2 ARCHIVAL IMAGES OF BATC, 2MASS, GALEX AND HST

In this section, we will determine the magnitudes of GC-1 and GC-2 based on the archival images of the BATC Multicolor Sky Survey, Two Micron All Sky Survey (2MASS) and Galaxy Evolution Explorer (GALEX) using a standard aperture photometry approach, i.e. the PHOT routine in DAOPHOT (Stetson 1987). In addition, we will also describe HST observations as well as magnitude transformation in this section.

2.1 Intermediate-band photometry

The M81 field is part of a galaxy calibration program of the BATC Multicolor Sky Survey. The BATC program uses the 60/90 cm Schmidt Telescope at the Xinglong Station of the National Astronomical Observatories, Chinese Academy of Sciences. This system includes 15 intermediate-band filters, covering a range of wavelength from 3000 to 10 000 Å (see Fan et al. 1996, for details). In order to study the stellar populations of GC-1 and GC-2, we extracted 322 images of M81 field as part of the BATC Multicolor Sky Survey, taken in 14 intermediate-band filters with a total exposure time of $\sim 100$ h from 1995 February 5 to 2002 April 30. These images were observed in the good nights including the photometric nights. The images of one filter were observed as possible as in the same night. The dome flat-field images were taken by using an isotropic diffuser right in front of the Schmidt corrector plate (the entrance pupil of the telescope) (see Zhou et al. 2004, for details). The images were reduced with standard procedures, including bias subtraction and flat-fielding of the CCD images, with an automatic data reduction software named PIPELINE I , developed for the BATC Multicolor Sky Survey (Fan et al. 1996; Zheng et al. 1999). Also in PIPELINE I , the astrometric plate solution is obtained by registering the brighter stars in each image with the HST Guide Star Catalogue (GSC) coordinate system (Jenkner et al. 1990). The positions of the stars in the images $(x$ and $y)$ then can be easily transformed to the equatorial coordinates $(\alpha$ and $\beta)$ in J2000. The final rms errors in positional accuracy of the stars are about 0.5 arcsec. Then, the multiple images of the same filter were combined to improve the signal-to-noise ratios (SNRs), and the cosmic rays and bad pixels were corrected by comparison of multiple images during combination. Before the combination, the other images were shifted and rotated according to one image. The images observed in different exposures were then stacked in the combination.

Calibration of the magnitude zero level in the BATC photometric system is similar to that of the spectrophotometric AB magnitude system. For flux calibration, the Oke–Gunn (Oke & Gunn 1983) primary flux standard stars HD 19445, HD 84937, BD +26 2606 and BD +17 4708 were observed during photometric nights (Yan et al. 2000). On the photometric nights, two or more standard stars as well as the BATC programmed fields were observed between air masses of 1 and 2. The standard stars are observed as frequently as possible using the central part of the CCD (size $300 \times 300$) for $\sim 100$ h from 1995 February 5 to 2002 April 30. These bright, isolated stars were taken by using a standard aperture photometry approach, i.e. the PHOT routine in DAOPHOT (Stetson 1987). In addition, we will also describe HST observations as well as magnitude transformation in this section.

Fig. 1 shows the finding charts of GC-1 and GC-2 in the BATC $g$ band. To determine the total luminosities of GC-1 and GC-2, we produced curves of growth from the $g$-band photometry obtained through apertures with radii in the range $2–11$ pixel with 1 pixel.
The local sky background was measured in an annulus with an inner radius 1 pixel larger than the photometric radius and 5 pixels wide. At last, the instrumental magnitudes were then calibrated using the relevant zero-points obtained from the photometric header keywords of each image. The calibrated photometry of GC-1 and GC-2 in \( J \), \( H \) and \( K_s \) bands is summarized in Table 2, in conjunction with the 1\( \sigma \) magnitude uncertainties obtained from DAOPHOT. The photometry of GC-1 in \( K_s \) cannot be obtained here because of low SNRs. In addition, since the observed magnitudes in the 2MASS photometric system are given in the Vega system, we transformed them to the AB system for our fits (see Section 3.3 for details). The photometric offsets in the 2MASS filters between the Vega and AB systems were obtained on the basis of equations (7) and (8) in the manual provided by Bruzual & Charlot (2003, hereafter BC03).

### 2.3 GALEX ultraviolet photometry

We used the GALEX archival images of GC-1 and GC-2 in the FUV and NUV bands to do photometry. The images were retrieved using the GALEX Batch Image Service.\(^2\) The exposure times were 14 706.7 s in the FUV band and 29 421.55 s in the NUV band, respectively. The images were sampled with 1.5 arcsec pixels. The relevant zero-points for photometry were 20.08 and 18.82 in the NUV and FUV magnitudes, respectively (Morrissey et al. 2007).

We determined the total luminosity of each object in the FUV and NUV bands using the processes given in Section 2.1. We produced a curve of growth from the NUV-band photometry obtained through apertures with radii in the range 2–13 pixel with 1 pixel increments. The calibrated photometry of GC-1 and GC-2 in the NUV band is summarized in Table 2. The photometry of GC-1 and GC-2 in the FUV band cannot be obtained here because of low SNRs. It is known that the GALEX photometric system is calibrated to match the spectrophotometric AB system (Rey et al. 2007) as the BATC photometric system does.

### 2.4 HST observation

The observations used here come from the HST program 11613 (P.I.: de Jong), in which GC-1 was observed by the HST/ACS/WFC in the F606W and F814W bands, and GC-2 was observed by the HST/Wide Field Camera 3 (WFC3)/UVIS in the F606W and F814W bands. GC-1 was observed with a total exposure time of 850 s in the F606W band and 690 s in the F814W band, and GC-2 was observed with a total exposure time of 735 s in the F606W band and 1225 s in the F814W band. We obtained the combined drizzled images from the Hubble Legacy Archive. In addition, for easy comparison with catalogues of the GCs in the Milky Way in the future work, we transform the ACS/WFC and WFC3/UVIS magnitudes in the F606W band to the standard \( V \) magnitude in their equation (7). However, till now transformations from WFC3/UVIS to standard \( V \) magnitude have not been presented in any references. We used equation (7) of Wang & Ma (2012) for the transformation in this paper, and \( V \) and \( I \) magnitudes are obtained in this paper (see Section 3.4 in detail). We rewrite equation (7) of Wang & Ma (2012) below:

\[
(V - F606W)_0 = -0.067 + 0.340(V - I)_0 - 0.038(V - I)_0^2.
\]  

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\(^1\) http://irsa.ipac.caltech.edu/applications/2MASS/IM/batch.html

\(^2\) http://galex.stsci.edu/GR6/
Figure 1. Images of GC-1 and GC-2 in the BATC g band obtained with the 60/90 cm Schmidt telescope. The circles are photometric apertures used in this paper.

Table 2. BATC, 2MASS and GALEX photometry of GC-1 and GC-2 in the M81 group.

<table>
<thead>
<tr>
<th>ID</th>
<th>b</th>
<th>c</th>
<th>d</th>
<th>e</th>
<th>f</th>
<th>g</th>
<th>h</th>
<th>i</th>
<th>j</th>
<th>k</th>
<th>m</th>
<th>n</th>
<th>o</th>
<th>p</th>
<th>J</th>
<th>H</th>
<th>Ks</th>
<th>NUV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.270</td>
<td>0.224</td>
<td>0.039</td>
<td>0.024</td>
<td>0.019</td>
<td>0.035</td>
<td>0.028</td>
<td>0.009</td>
<td>0.030</td>
<td>0.033</td>
<td>0.038</td>
<td>0.072</td>
<td>0.104</td>
<td>0.029</td>
<td>0.021</td>
<td>–</td>
<td>0.427</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.106</td>
<td>0.112</td>
<td>0.017</td>
<td>0.011</td>
<td>0.010</td>
<td>0.016</td>
<td>0.011</td>
<td>0.005</td>
<td>0.014</td>
<td>0.015</td>
<td>0.013</td>
<td>0.028</td>
<td>0.051</td>
<td>0.017</td>
<td>0.014</td>
<td>0.012</td>
<td>0.290</td>
<td></td>
</tr>
</tbody>
</table>

We will use these HST images to derive the structural and dynamical parameters of GC-1 and GC-2 (see Sections 4 and 5 for details).

3 STELLAR POPULATION

3.1 Metallicities and reddening values

Cluster SEDs are determined by the combination of their ages and metallicities, which is often referred to as the age–metallicity degeneracy. Therefore, the age of a cluster can only be constrained accurately if the metallicity is determined independently with confidence. For GC-1 and GC-2, only Jang et al. (2012) determined their metallicities. These authors presented the colour–magnitude diagrams for GC-1 and GC-2, and derived the metallicities to be \([\text{Fe}/\text{H}] = -2.23\pm0.11\) for GC-1 and \([\text{Fe}/\text{H}] = -2.23\pm0.12\) for GC-2 based on the mean colour of the red giant branch stars. In addition, Jang et al. (2012) derived the metallicity of GC-2 to be \([\text{Fe}/\text{H}] = -2.3\pm0.12\) based on its optical spectrum observed by the Sloan Digital Sky Survey (SDSS). Here, we adopted the values of metallicity from Jang et al. (2012): \([\text{Fe}/\text{H}] = -2.23\pm0.11\) for GC-1 and \([\text{Fe}/\text{H}] = -2.23\pm0.12\) for GC-2.

To determine the ages and masses of GC-1 and GC-2, we compared their SEDs with theoretical stellar population-synthesis models. The SEDs consist of photometric data in the NUV band of GALEX, 14 BATC intermediate-band and 2MASS near-infrared (NIR) JHKs filters obtained in this paper. GC-1 and GC-2 are both very metal poor (see Section 3.1). So, we use the SSP models of BC03, which provide the evolution of the spectra and photometric properties for a wide range of stellar metallicities. For example, BC03 SSP models based on the Padova-1994 evolutionary tracks include six initial metallicities: \(Z = 0.0001, 0.0004, 0.004, 0.008, 0.02\) and \(0.05 (Z_\odot)\), corresponding to \([\text{Fe}/\text{H}] = -2.25, -1.65, -0.64, -0.33, +0.09\) and \(+0.56\). In this paper, we adopt the high-resolution SSP models using the Padova-1994 evolutionary tracks to determine the most appropriate ages for GC-1 and GC-2. And a Salpeter (1955) initial mass function (IMF) is also used. These SSP models contain 221 spectra describing the spectral evolution of SSPs from \(1.0 \times 10^5\) yr to 20 Gyr. The evolving spectra include the contribution of the stellar component at wavelengths from 91 Å to 160 µm.

Since our observational data are integrated luminosities through a given set of filters, we convolved the theoretical SSP SEDs of Schlegel, Finkbeiner & Davis (1998) presents \(E(B-V) = 0.09\) for GC-1 and \(E(B-V) = 0.10\) for GC-2 (see also Jang et al. 2012 and Monachesi et al. 2013).
BC03 with the GALEX NUV, BATC b − p and 2MASS JHK, filter response curves to obtain synthetic optical and NIR photometry for comparison. The synthetic \( \nu \)th filter magnitude can be computed by

\[
m = -2.5 \log \left( \int F_{\nu} \varphi_{\nu}(\lambda) d\lambda \right) - 48.60,
\]

where \( F_{\nu} \) is the theoretical SED, and \( \varphi_{\nu} \) is the response function of the \( \nu \)th filter of the GALEX, BATC and 2MASS photometric systems. Here, \( F_{\nu} \) varies with age and metallicity.

### 3.3 Fit results

We use a \( \chi^2 \) minimization approach to examine which SSP models are most compatible with the observed SEDs of GC-1 and GC-2, following

\[
\chi^2 = \sum_{i=1}^{N} \left( \frac{m_{\text{intr}}^{\nu}(t) - m_{\text{mod}}^{\nu}(t)}{\sigma_i} \right)^2,
\]

where \( m_{\text{intr}}^{\nu}(t) \) is the integrated magnitude in the \( \nu \)th filter of a theoretical SSP at age \( t \), \( m_{\text{mod}}^{\nu}(t) \) represents the intrinsic integrated magnitude in the same filter, and

\[
\sigma_i^2 = \sigma_{\text{obs},i}^2 + \sigma_{\text{mod},i}^2 + \sigma_{\text{md},i}^2,
\]

Here, \( \sigma_{\text{obs},i} \) is the observational uncertainty from Table 2 of this paper, \( \sigma_{\text{mod},i} \) is the uncertainty associated with the model itself and \( \sigma_{\text{md},i} \) is associated with the uncertainty with the distance modulus adopted here. Following Ma et al. (2012), we adopt \( \sigma_{\text{mod},i} = 0.05 \) mag. For \( \sigma_{\text{md},i} \), we adopt 0.03 and 0.04 for GC-1 and GC-2, respectively, which are from Jang et al. (2012). \( N \) is the number of photometries used in the fitting.

Before fitting, we obtained the theoretical SEDs for the metallicity [Fe/H] = −2.23 by model interpolation of between [Fe/H] = −2.25 and −1.65 models for GC-1. For GC-2, we used the theoretical SEDs for the metallicity [Fe/H] = −2.25 model for fitting.

For every fit we obtain a value for the reduced \( \chi^2 \), and \( \chi^2 = \chi^2/\nu \), where \( \nu \) is the number of free parameters, i.e. the number of observational data points minus the number of parameters used in the theoretical model. For a good fit, \( \chi^2 \) should be about unity. The fit with the minimum value of \( \chi^2 \) [hereafter \( \chi^2(\text{min}) \)] was adopted as the best fit and age was adopted. This method was applied for fits with the BC03 models. To estimate the uncertainty in the determined age we use confidence limits. If \( \chi^2 < \chi^2(\text{min}) + 1 \) then the resulting age is within the 68.3 per cent probability range. So the accepted range in age is derived from the fits which have \( \chi^2(\text{min}) < \chi^2 < \chi^2(\text{min}) + 1 \). With this method we derived the ages with their uncertainties of GC-1 and GC-2. For GC-1, the best-reduced \( \chi^2(\text{min}) = 0.7 \) is achieved with an age of 15.50 ± 3.20 Gyr when the value of \( E(B-V) \) is adopted to be 0.09, and \( \nu = 16 \). For GC-2, the best-reduced \( \chi^2(\text{min}) = 2.9 \) is achieved with an age of 15.10 ± 2.70 Gyr when the value of \( E(B-V) \) is adopted to be 0.10, and \( \nu = 16 \). The values for the extinction coefficient, \( R_\nu \), are obtained by interpolating the interstellar extinction curve of Cardelli, Clayton & Mathis (1989). Fig. 2 shows the intrinsic SEDs of GC-1 and GC-2, the integrated SEDs of the best-fitting models and the spectra of the best-fitting models. From Fig. 2, we can see that, for GC-2, the BC03 SSP models cannot fit the photometric datum in the \( c \) band as well as the other 17 photometric data, i.e. the observed magnitude is dimmer than that of the model in the \( c \) band. We have not been able to identify the cause of this discrepancy. Direct inspection of the image in the \( c \) band clearly shows that GC-2 is not unusual. Also, we used the same image to determine the photometries for GC-1 and GC-2 at the same time. So, we argued that this discrepancy may be from the intrinsic property of GC-2, i.e. it is caused by the intrinsic luminosity of stellar populations of GC-2. In the fitting, we did not use the magnitude in the \( c \) band. In addition, it is evident that the ages of GC-1 and GC-2 obtained here based on the BC03 models are greater than the currently accepted age of the universe. However, we must keep in mind that the BC03 SSP models were calculated for ages up to 20 Gyr. In fact, ages derived for objects such as GCs and galaxies in excess of that of the universe only mean that these objects are among the oldest objects in the universe.

### 3.4 Masses

We next determine the masses of GC-1 and GC-2. The BC03 SSP models are normalized to a total mass of 1 M\(_{\odot}\) in stars at age \( t = 0 \). The absolute magnitudes (in the Vega system) in \( UBVRI \) and 2MASS JHK, filters are included in the BC03 SSP models. The difference between the intrinsic absolute magnitudes and those given by the model provides a direct measurement of the cluster mass. To
reduce mass uncertainties resulting from photometric uncertainties based on only magnitudes in one filter (in general the V band is used), we estimated the masses of GC-1 and GC-2 using magnitudes in the UBVRI and JHK bands. Zhou et al. (2003) have derived the relationships between the BATC intermediate-band system and the broad-band system. However, we cannot derive the magnitudes in the U band since the magnitudes in the a band cannot be obtained in this paper. The magnitudes in the BVR magnitudes are obtained using the photometries of the BATC intermediate-band system obtained here (see Table 2 for details) and the relationships between these two systems in Zhou et al. (2003). The BVR magnitudes are $B = 19.42 \pm 0.083$, $V = 18.71 \pm 0.032$, $R = 18.43 \pm 0.003$ and $I = 17.73 \pm 0.025$ for GC-1, and $B = 18.60 \pm 0.039$, $V = 17.79 \pm 0.016$, $R = 17.51 \pm 0.005$ and $I = 16.78 \pm 0.001$ for GC-2. The resulting mass determinations for GC-1 and GC-2 are listed in Table 3 with their 1σ uncertainties. Table 3 shows that the masses of GC-1 and GC-2 obtained based on the magnitudes in different bands are consistent.

### 4 HST DATA ANALYSIS

#### 4.1 Ellipticity, position angle and surface brightness profile

The imaging data that we used in this work to obtain the structural and dynamical parameters of GC-1 and GC-2 come from the HST observations in the F606W and F814W bands (see Section 2.4 for details). The data analysis procedures used to measure the surface brightness profiles of clusters have been described in Barmby et al. (2007); here we briefly summarize the procedures. The surface photometries of each cluster were obtained from the drizzled images using the IRAF task ELLIPSE. The centre position of each cluster was fixed at a value derived by the object locator of the ELLIPSE task; however an initial centre position was determined by centroiding. Elliptical isophotes were fitted to the data, with no sigma clipping. The isophote semimajor axis. In the second pass the surface brightness harmonics. The ellipticities and PAs measured on images in different filters track well together, as we would expect. Figs 3 and 4 show that the PAs are occasionally wildly varying. This is likely to be produced by internal errors in the ELLIPSE task. The final ellipticity and PA for each cluster were calculated as the average of the values obtained in the first pass of ELLIPSE task, which are listed in Table 4. Errors correspond to the standard deviation of the mean. From Figs 3 and 4, and Table 4, we can see that the ellipticities of GC-1 and GC-2 are less than 0.1, which are consistent with the mean value of 0.07 ± 0.01 for the Milky Way GCs (White & Shawl 1987) and the mean $\epsilon = 0.11 \pm 0.01$ for the M31 GCs (Barmby, Holland & Huchra 2002).

Raw output from package ELLIPSE is in terms of counts s$^{-1}$ pixel$^{-1}$, which needs to be multiplied by a number (400 for ACS/WFC and 625 for WFC3/UVIS) to convert to counts s$^{-1}$ arcsec$^{-2}$. A formula is used to transform the counts to surface brightness in magnitudes calibrated on the VEGAMAG system,

$$\mu/\text{mag arcsec}^{-2} = -2.5 \log(\text{counts s}^{-1}\text{arcsec}^{-2}) + \text{zero-point}.\quad (5)$$

#### Table 3. Mass estimates of GC-1 and GC-2 based on the BC03 models.

<table>
<thead>
<tr>
<th></th>
<th>$B$</th>
<th>$V$</th>
<th>$R$</th>
<th>$I$</th>
<th>$J$</th>
<th>$H$</th>
<th>$K_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>GC-1</td>
<td>1.93 ± 0.15</td>
<td>1.97 ± 0.06</td>
<td>1.77 ± 0.01</td>
<td>2.04 ± 0.05</td>
<td>1.87 ± 0.05</td>
<td>2.04 ± 0.04</td>
<td>–</td>
</tr>
<tr>
<td>GC-2</td>
<td>5.20 ± 0.19</td>
<td>5.81 ± 0.09</td>
<td>5.25 ± 0.02</td>
<td>6.08 ± 0.01</td>
<td>6.78 ± 0.11</td>
<td>5.61 ± 0.07</td>
<td>7.11 ± 0.08</td>
</tr>
</tbody>
</table>

Figure 3. Ellipticity ($\epsilon$) and PA as a function of the semimajor axis ($a$) in the F606W and F814W filters of HST/ACS/WFC for GC-1.

Figure 4. Ellipticity ($\epsilon$) and PA as a function of the semimajor axis ($a$) in the F606W and F814W filters of HST/WFC3/UVIS for GC-2.
μ/ness in magnitude was done according to Calibration data for the Column 7 gives a flag for each point, which has the same meaning as Additive conversion between surface brightness in magnitude in mag and magnitude in mag arcsec−2. Updated absolute magnitude of the Sun (C. Willmer, private communication)−2. Additive conversion between surface brightness in counts s−1 and intensity in L⊙ pc−2. Coefficientc of the PSF as Barmby et al. (2007) and Wang & Ma (2013) did. With updated absolute magnitudes of the Sun, M⊙ (C. Willmer, private communication)−1 arcsec−2 and intensity in L⊙ pc−2.c Updated absolute magnitude of the Sun (C. Willmer, private communication).d Multiplicative conversion between surface brightness in counts s−1 and intensity in L⊙ pc−2.d Conversion factor (7) for transforming counts to surface brightness in luminosity density in L⊙ pc−2.× conversion factor × (counts s−1 arcsec−2). Conversion from luminosity density in L⊙ pc−2 to surface brightness in magnitude was done according to

\[ \mu / \text{mag arcsec}^{-2} = -2.5 \log (I / L_\odot \text{ pc}^{-2}) + \text{coefficient}. \]  

The zero-points, conversion factors and coefficients used in these transformations for each filter are also listed in Table 5. In this paper, the final, calibrated intensity profiles for GC-1 and GC-2 with no extinction correction are listed in Table 6. The reported intensities are calibrated on the VEGAMAG scale. In Table 6, Column 7 gives a flag for each point, which has the same meaning as defined by Barmby et al. (2007) and Mclaughlin et al. (2008). The points flagged with ‘OK’ are used to constrain the model fit, while the points flagged with ‘DEP’ are those that may lead to excessive weighting of the central regions of clusters (see Barmby et al. 2007; Mclaughlin et al. 2008, for details). In addition, points marked with ‘BAD’ are those individual isophotes that deviated strongly from their neighbours or showed irregular features, which were deleted by hand.

To convert from intensity in L⊙ pc−2 to surface brightness in counts s−1 arcsec−2, use the following relationship:

\[ I / L_\odot \text{ pc}^{-2} = \text{conversion factor} \times (\text{counts s}^{-1} \text{ arcsec}^{-2}). \]  

As noted by Barmby et al. (2007), occasional oversubtraction of the background during the multidrizzling in the automatic reduction pipeline leads to ‘negative’ counts in some pixels, so we worked in the background during the multidrizzling in the automatic reduction pipeline.

Note: This table is available in its entirely in machine-readable form.
4.3 Extinction and magnitude transformation

When we fit models to the surface brightness profiles of GC-1 and GC-2, we correct the intensity profiles for extinction. Table 5 lists the effective wavelengths of the ACS/WFC and WFC3/UVIS filters from the Instrument Handbook. With the extinction curve taken from Cardelli et al. (1989) with RV = 3.1, we derived the A_r values for each filter. The reddening values of GC-1 and GC-2 mentioned and used in Section 3 are listed in Table 4.

5 MODEL FITTING

5.1 Structural models

As was done by Barmby et al. (2007), McLaughlin et al. (2008), Wang & Ma (2013) and Ma (2015), we used three structural models to fit surface profiles of GC-1 and GC-2. These models are developed by King (1966), Wilson (1975) and Sérsic (1968) (hereafter the ‘King model’, ‘Wilson model’ and ‘Sérsic model’, respectively).

Table 7. Coefficients for the PSF models.

<table>
<thead>
<tr>
<th>Detector</th>
<th>Filter</th>
<th>r_0</th>
<th>α</th>
<th>β</th>
</tr>
</thead>
<tbody>
<tr>
<td>(arcsec)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
<td>(4)</td>
<td>(5)</td>
</tr>
<tr>
<td>ACS/WFC</td>
<td>F606W</td>
<td>0.053</td>
<td>3</td>
<td>3.14</td>
</tr>
<tr>
<td></td>
<td>F814W</td>
<td>0.056</td>
<td>3</td>
<td>3.05</td>
</tr>
<tr>
<td>WFC3/UVIS</td>
<td>F606W</td>
<td>0.050</td>
<td>3</td>
<td>3.24</td>
</tr>
<tr>
<td></td>
<td>F814W</td>
<td>0.058</td>
<td>3</td>
<td>3.50</td>
</tr>
</tbody>
</table>

5.2 Fits

After the intensity profiles were corrected for extinction (see Section 4.3 for details), we fitted models to the brightness profiles of GC-1 and GC-2.

We first convolved the three models with PSFs for the filters used. Given a value for the scale radius r_0, we computed a dimensionless model profile I_{mod} = I_{mod}/I_0 and then performed the convolution,

\[ \tilde{I}_{mod}(R/r_0) = \int \int \tilde{I}_{mod}(R/r_0, \tilde{r}_{PSF}) \, \lambda(\xi - x', \eta - y') \, dx' \, dy', \]

where \( R = x^2 + y^2 \) and \( R' = x^2 + y^2 \). \( \tilde{r}_{PSF} \) was approximated using equation 4 of Wang & Ma (2013) (see McLaughlin et al. 2008, for details). The best-fitting model was derived by calculating and minimizing \( \chi^2 \) as the sum of squared differences between model intensities and observed intensities with the extinction corrected, \( \chi^2 = \sum_i \frac{(I_{obs}(R_i) - I_{mod}(R_i,r_0) - I_{bkg})^2}{\sigma_i^2} \),

in which a background I_{bkg} was also fitted. The uncertainties of observed intensities listed in Table 6 were used as weights.

We plot the fitting for GC-1 and GC-2 in Figs 5 and 6. The observed intensity profile with extinction corrected is plotted as a function of logarithmic projected radius. The open squares are the data points included in the model fitting, while the crosses are points flagged as ‘DEP’ or ‘BAD’, which are not used to constrain the fit. Dashed (blue) curves trace the PSF intensity profile; bold dash–dotted curves, the unconvolved best-fitting model and solid (red) curves, the PSF-convolved best fits.

5.3 Main model parameters and derived qualities

Table 8 lists the basic ingredients of all model fits to GC-1 and GC-2, with a simple description of each parameter/column at the end. Error bars on all these parameters (and those on all the derived quantities below) are defined in the same way as in McLaughlin et al. (2008).

Table 9 contains a number of other structural cluster properties derived from the basic fit parameters given in Table 8, with a simple description of each parameter/column at the end.
Table 8. Basic parameters of GC-1 and GC-2 in the M81 group.

<table>
<thead>
<tr>
<th>ID</th>
<th>Detector</th>
<th>Band</th>
<th>$N_{gfs}$</th>
<th>Model</th>
<th>$\chi^2_\text{min}$</th>
<th>$I_{bhkg}$</th>
<th>$W_0^d$</th>
<th>$c/n^e$</th>
<th>$\mu^f_0$</th>
<th>log $r_0^g$</th>
<th>log $r_0^h$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(L⊙ pc⁻²)</td>
<td>(mag arcsec⁻²)</td>
<td>(arcsec)</td>
<td>(arcsec)</td>
<td>(pc)</td>
<td></td>
</tr>
<tr>
<td>GC-1</td>
<td>ACS/WFC</td>
<td>606</td>
<td>40</td>
<td>K66</td>
<td>48.87</td>
<td>2.90 ± 1.20</td>
<td>8.50^{+0.60}_{-0.57}</td>
<td>1.98^{+0.16}_{-0.17}</td>
<td>16.11^{+0.25}_{-0.15}</td>
<td>−1.450^{+0.005}_{-0.007}</td>
<td>−0.205^{+0.015}_{-0.017}</td>
</tr>
<tr>
<td></td>
<td>ACS/WFC</td>
<td>814</td>
<td>38</td>
<td>K66</td>
<td>32.07</td>
<td>4.00 ± 1.98</td>
<td>8.60^{+0.57}_{-0.51}</td>
<td>2.01^{+0.15}_{-0.14}</td>
<td>15.45^{+0.17}_{-0.14}</td>
<td>−1.500^{+0.01}_{-0.005}</td>
<td>−0.255^{+0.031}_{-0.005}</td>
</tr>
<tr>
<td>GC-2</td>
<td>WFC3/UVIS</td>
<td>606</td>
<td>46</td>
<td>K66</td>
<td>30.25</td>
<td>2.70 ± 1.02</td>
<td>8.20^{+0.30}_{-0.28}</td>
<td>1.89^{+0.09}_{-0.13}</td>
<td>15.83^{+0.10}_{-0.06}</td>
<td>−1.100^{+0.031}_{-0.030}</td>
<td>0.193^{+0.015}_{-0.015}</td>
</tr>
<tr>
<td></td>
<td>WFC3/UVIS</td>
<td>814</td>
<td>46</td>
<td>K66</td>
<td>22.97</td>
<td>3.40 ± 0.90</td>
<td>7.90^{+0.25}_{-0.27}</td>
<td>1.80^{+0.07}_{-0.08}</td>
<td>15.22^{+0.10}_{-0.08}</td>
<td>−1.050^{+0.021}_{-0.018}</td>
<td>0.243^{+0.021}_{-0.018}</td>
</tr>
</tbody>
</table>

---

$^a$The number of points in the intensity profile that were used for constraining the model fits.

$^b$The minimum $\chi^2$ obtained in the fits.

$^c$The best fitted background intensity.

$^d$The dimensionless central potential of the best-fitting model, defined as $W_0 = -\phi(0)/\sigma^2$.

$^e$The concentration $c = \log (r_0/r_0)$.

$^f$The best-fitting central surface brightness in the native bandpass of the data.

$^g$The best model fit scale radius $r_0$ in arcsec.

$^h$The best model fit scale radius $r_0$ in parsec.

The uncertainties on all of these derived parameters were estimated in the same way as in Mlaughlin et al. (2008). The uncertainties of each parameter/column at the end, and the details of the calculations are presented in Mlaughlin et al. (2008). The uncertainties are independent.

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5.4 Comparison of fits in the F606W and F814W bands

In this paper, we derived the structural and dynamical parameters from fitting three different models (King 1966, Wilson 1975 and Sérsic 1968) to the radial surface brightness profiles of GC-1 and GC-2 in the F606W and F814W bands. Assessment of the systematic errors and colour dependences in the fits can be done by comparing model fits to the same cluster observed in different bands (Barmby et al. 2007). Fig. 7 compares the parameters derived from fits to GC-1 and GC-2 observed in both the F606W and F814W bands. It is obvious that the agreement is quite good, with somewhat larger scatter for the Wilson (1975) model fits to GC-2 in the projected half-light radius. For both the projected half-light radius and ratio of half-light to core radius, the agreement is excellent for the Sérsic.
Table 9. Derived structural and photometric parameters of GC-1 and GC-2 in the M81 group.

<table>
<thead>
<tr>
<th>ID</th>
<th>Detector</th>
<th>Band</th>
<th>Model</th>
<th>$\log r_t^a$ (pc)</th>
<th>$\log R_e^b$ (pc)</th>
<th>$\log R_e^c$ (pc)</th>
<th>$\log R_R^d$ (L☉, V pc$^{-2}$)</th>
<th>$\log I^e_v$ (L☉, V pc$^{-3}$)</th>
<th>$\log I^f_v$ (L☉, V pc$^{-3}$)</th>
<th>$\log L^g_v$ (L☉, V pc$^{-3}$)</th>
<th>$V^h_v$ (mag)</th>
<th>$\log h^i_v$ (L☉, V pc$^{-2}$)</th>
<th>$\langle \mu_v \rangle^j_h$ (mag arcsec$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GC-1</td>
<td>ACS/WFC</td>
<td>606</td>
<td>K66</td>
<td>-0.17 ±0.24</td>
<td>-0.05 ±0.16</td>
<td>0.740 ±0.196</td>
<td>0.955 ±0.250</td>
<td>4.02 ±0.10</td>
<td>3.93 ±0.12</td>
<td>5.63 ±0.04</td>
<td>18.51 ±0.07</td>
<td>3.35 ±0.26</td>
<td>17.98 ±0.88</td>
</tr>
<tr>
<td>W</td>
<td>-0.18</td>
<td>-0.18</td>
<td>0.876</td>
<td>0.14 ±0.14</td>
<td>0.14 ±0.14</td>
<td>1.003 ±0.254</td>
<td>4.05 ±0.013</td>
<td>3.87 ±0.04</td>
<td>5.74 ±0.04</td>
<td>18.24 ±0.012</td>
<td>3.19 ±0.08</td>
<td>18.39 ±0.81</td>
<td>17.74 ±0.40</td>
</tr>
<tr>
<td>S</td>
<td>∞</td>
<td>-0.18</td>
<td>0.669</td>
<td>-0.09 ±0.06</td>
<td>-0.09 ±0.06</td>
<td>0.925 ±0.197</td>
<td>4.05 ±0.10</td>
<td>5.05 ±0.11</td>
<td>5.64 ±0.08</td>
<td>18.47 ±0.015</td>
<td>3.45 ±0.21</td>
<td>17.96 ±0.83</td>
<td>17.74 ±0.40</td>
</tr>
<tr>
<td>ACS/WFC</td>
<td>814</td>
<td>K66</td>
<td>-0.24</td>
<td>-0.06 ±0.11</td>
<td>-0.06 ±0.11</td>
<td>0.736 ±0.188</td>
<td>1.000 ±0.250</td>
<td>3.98 ±0.13</td>
<td>3.36 ±0.26</td>
<td>17.96 ±0.83</td>
<td>3.18 ±0.04</td>
<td>18.41 ±0.09</td>
<td>17.74 ±0.40</td>
</tr>
<tr>
<td>W</td>
<td>-0.15</td>
<td>-0.24</td>
<td>0.882</td>
<td>-0.21 ±0.11</td>
<td>-0.19 ±0.11</td>
<td>0.693 ±0.238</td>
<td>1.009 ±0.249</td>
<td>3.87 ±0.04</td>
<td>3.18 ±0.04</td>
<td>18.41 ±0.09</td>
<td>3.18 ±0.04</td>
<td>18.41 ±0.09</td>
<td>17.74 ±0.40</td>
</tr>
<tr>
<td>S</td>
<td>∞</td>
<td>-0.24</td>
<td>0.693</td>
<td>-0.14 ±0.12</td>
<td>-0.14 ±0.12</td>
<td>0.693 ±0.238</td>
<td>1.009 ±0.249</td>
<td>3.87 ±0.04</td>
<td>3.18 ±0.04</td>
<td>18.41 ±0.09</td>
<td>3.18 ±0.04</td>
<td>18.41 ±0.09</td>
<td>17.74 ±0.40</td>
</tr>
<tr>
<td>GC-2</td>
<td>WFC3/UVIS</td>
<td>606</td>
<td>K66</td>
<td>-0.35 ±0.11</td>
<td>-0.05 ±0.15</td>
<td>0.268 ±0.007</td>
<td>0.736 ±0.188</td>
<td>4.13 ±0.03</td>
<td>3.65 ±0.05</td>
<td>6.16 ±0.03</td>
<td>17.42 ±0.07</td>
<td>3.37 ±0.14</td>
<td>17.93 ±0.34</td>
</tr>
<tr>
<td>W</td>
<td>0.24 ±0.17</td>
<td>-0.18</td>
<td>0.326</td>
<td>-0.08 ±0.12</td>
<td>-0.12 ±0.12</td>
<td>1.130 ±0.100</td>
<td>0.862 ±0.106</td>
<td>4.11 ±0.03</td>
<td>3.53 ±0.03</td>
<td>6.25 ±0.03</td>
<td>17.21 ±0.11</td>
<td>3.19 ±0.07</td>
<td>18.39 ±0.41</td>
</tr>
<tr>
<td>S</td>
<td>∞</td>
<td>-0.15</td>
<td>0.970</td>
<td>-0.11 ±0.19</td>
<td>-0.19 ±0.19</td>
<td>0.736 ±0.238</td>
<td>1.009 ±0.249</td>
<td>3.87 ±0.04</td>
<td>3.18 ±0.04</td>
<td>18.41 ±0.09</td>
<td>3.18 ±0.04</td>
<td>18.41 ±0.09</td>
<td>17.74 ±0.40</td>
</tr>
<tr>
<td>WFC3/UVIS</td>
<td>814</td>
<td>K66</td>
<td>-0.07</td>
<td>-0.04 ±0.14</td>
<td>-0.04 ±0.14</td>
<td>0.251 ±0.004</td>
<td>1.042 ±0.071</td>
<td>4.17 ±0.04</td>
<td>4.61 ±0.07</td>
<td>6.15 ±0.07</td>
<td>17.46 ±0.17</td>
<td>3.41 ±0.17</td>
<td>17.84 ±0.44</td>
</tr>
<tr>
<td>W</td>
<td>0.34 ±0.14</td>
<td>-0.07</td>
<td>0.315</td>
<td>-0.06 ±0.04</td>
<td>-0.06 ±0.04</td>
<td>0.229 ±0.019</td>
<td>0.727 ±0.132</td>
<td>3.66 ±0.05</td>
<td>3.45 ±0.12</td>
<td>17.74 ±0.51</td>
<td>3.45 ±0.12</td>
<td>17.74 ±0.30</td>
<td>17.84 ±0.44</td>
</tr>
<tr>
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<td>∞</td>
<td>-0.07</td>
<td>0.957</td>
<td>-0.15 ±0.15</td>
<td>-0.15 ±0.15</td>
<td>0.969 ±0.196</td>
<td>0.926 ±0.197</td>
<td>3.45 ±0.04</td>
<td>3.37 ±0.14</td>
<td>17.95 ±0.25</td>
<td>3.45 ±0.14</td>
<td>17.95 ±0.25</td>
<td>17.84 ±0.44</td>
</tr>
</tbody>
</table>

---

$a$ The model tidal radius $r_t$ in parsec.

$b$ The projected core radius of the model fitting a cluster, defined as $R_c = I_0/2$.

$c$ The projected half-light, or effective radius of a model, containing half the total luminosity in projection.

$d$ A measure of cluster concentration and relatively more model-independent than $W_0$ or $c$.

$e$ The best-fitting central ($R = 0$) luminosity surface density in the $V$ band, defined as $\log I_v = 0.4(26.358 - \mu_v)$, where 26.358 is the ‘coefficient’ corresponding to a solar absolute magnitude $M_v, 0 = +4.786$ (C. Willner, private communication).

$f$ The central ($r = 0$) luminosity volume density in the $V$ band.

$g$ The $V$-band total integrated model luminosity.

$h$ The total $V$-band magnitude of a model cluster, defined as $V_{500} = 4.786 - 2.5\log (L_v/L_{500}) + 5\log (D/10$ pc).

$i$ The luminosity surface density averaged over the half-light/effective radius in the $V$ band, defined as $\log h_v = \log (L_v / 2\pi R_e^5)$. 

$j$ The surface brightness in magnitude over the half-light/effective radius in the $V$ band, defined as $\langle \mu_v \rangle_h = 26.358 - 2.5\log h_v$. 

Note: The parameters are given with uncertainties.
Table 10. Derived dynamical parameters of GC-1 and GC-2 in the M81 group.

<table>
<thead>
<tr>
<th>ID</th>
<th>Detector</th>
<th>Band</th>
<th>Model</th>
<th>log $M_{\text{tot}}/\text{M}_\odot$</th>
<th>log $E_\text{ej}$/erg</th>
<th>log $\Sigma_0$/$\text{M}_\odot$ pc$^{-2}$</th>
<th>log $\rho_0$/$\text{M}_\odot$ pc$^{-2}$</th>
<th>log $\Sigma_b$/$\text{M}_\odot$ pc$^{-2}$</th>
<th>log $\sigma_p$/$\text{km s}^{-1}$</th>
<th>log $v_{\text{esc}}$/$\text{km s}^{-1}$</th>
<th>log $t_{\text{esc}}$/yr</th>
<th>log $f_{\odot}$/yr$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(1)</td>
<td>(5)</td>
<td>(7)</td>
<td>(9)</td>
<td>(11)</td>
<td>(13)</td>
<td>(15)</td>
<td>(17)</td>
<td>(19)</td>
</tr>
<tr>
<td>GC-1</td>
<td>ACS/WFC</td>
<td></td>
<td></td>
<td>1.935$^{+0.238}_{-0.247}$</td>
<td>K66</td>
<td>5.92$^{+0.06}_{-0.07}$</td>
<td>0.43$^{+0.22}_{-0.33}$</td>
<td>4.31$^{+0.08}_{-0.12}$</td>
<td>2.22$^{+0.13}_{-0.14}$</td>
<td>3.64$^{+0.15}_{-0.26}$</td>
<td>0.786$^{+0.036}_{-0.048}$</td>
<td>1.409$^{+0.011}_{-0.026}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>W</td>
<td></td>
<td></td>
<td>6.03$^{+0.06}_{-0.08}$</td>
<td>50.67$^{+0.32}_{-0.25}$</td>
<td>4.34$^{+0.06}_{-0.07}$</td>
<td>4.16$^{+0.06}_{-0.07}$</td>
<td>3.47$^{+0.26}_{-0.29}$</td>
<td>0.846$^{+0.027}_{-0.032}$</td>
<td>1.46$^{+0.017}_{-0.025}$</td>
<td>9.81$^{+0.029}_{-0.024}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S</td>
<td></td>
<td></td>
<td>5.93$^{+0.10}_{-0.09}$</td>
<td>48.4$^{+0.29}_{-0.40}$</td>
<td>4.33$^{+0.09}_{-0.11}$</td>
<td>5.34$^{+0.12}_{-0.13}$</td>
<td>3.74$^{+0.23}_{-0.27}$</td>
<td>0.131$^{+0.009}_{-0.012}$</td>
<td>0.96$^{+0.028}_{-0.049}$</td>
<td>9.50$^{+0.029}_{-0.026}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.935$^{+0.238}_{-0.247}$</td>
<td>K66</td>
<td>50.30$^{+0.21}_{-0.33}$</td>
<td>4.27$^{+0.14}_{-0.14}$</td>
<td>3.65$^{+0.34}_{-0.36}$</td>
<td>0.761$^{+0.047}_{-0.056}$</td>
<td>1.387$^{+0.028}_{-0.036}$</td>
<td>9.55$^{+0.030}_{-0.028}$</td>
<td>0.772$^{+0.013}_{-0.008}$</td>
</tr>
<tr>
<td>GC-2</td>
<td>WFC3/UVIS</td>
<td></td>
<td></td>
<td>1.939$^{+0.236}_{-0.249}$</td>
<td>K66</td>
<td>6.45$^{+0.07}_{-0.08}$</td>
<td>51.79$^{+0.21}_{-0.24}$</td>
<td>4.42$^{+0.07}_{-0.07}$</td>
<td>3.94$^{+0.07}_{-0.09}$</td>
<td>3.66$^{+0.16}_{-0.15}$</td>
<td>1.04$^{+0.027}_{-0.031}$</td>
<td>1.65$^{+0.020}_{-0.022}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>W</td>
<td></td>
<td></td>
<td>6.53$^{+0.06}_{-0.08}$</td>
<td>51.91$^{+0.21}_{-0.25}$</td>
<td>4.40$^{+0.06}_{-0.07}$</td>
<td>3.82$^{+0.07}_{-0.06}$</td>
<td>3.48$^{+0.23}_{-0.17}$</td>
<td>1.07$^{+0.027}_{-0.033}$</td>
<td>1.68$^{+0.028}_{-0.035}$</td>
<td>10.41$^{+0.017}_{-0.022}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S</td>
<td></td>
<td></td>
<td>6.43$^{+0.09}_{-0.08}$</td>
<td>50.01$^{+0.30}_{-0.32}$</td>
<td>4.46$^{+0.07}_{-0.09}$</td>
<td>4.89$^{+0.08}_{-0.10}$</td>
<td>3.69$^{+0.18}_{-0.18}$</td>
<td>0.45$^{+0.044}_{-0.035}$</td>
<td>1.26$^{+0.025}_{-0.035}$</td>
<td>10.12$^{+0.023}_{-0.024}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.939$^{+0.236}_{-0.249}$</td>
<td>K66</td>
<td>51.89$^{+0.21}_{-0.25}$</td>
<td>3.89$^{+0.09}_{-0.09}$</td>
<td>3.74$^{+0.21}_{-0.13}$</td>
<td>1.065$^{+0.028}_{-0.031}$</td>
<td>1.67$^{+0.028}_{-0.034}$</td>
<td>10.11$^{+0.019}_{-0.022}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>W</td>
<td></td>
<td></td>
<td>52.01$^{+0.21}_{-0.25}$</td>
<td>3.77$^{+0.06}_{-0.07}$</td>
<td>3.65$^{+0.15}_{-0.12}$</td>
<td>1.095$^{+0.027}_{-0.034}$</td>
<td>1.70$^{+0.028}_{-0.035}$</td>
<td>10.27$^{+0.015}_{-0.014}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>S</td>
<td></td>
<td></td>
<td>50.01$^{+0.27}_{-0.31}$</td>
<td>4.89$^{+0.09}_{-0.10}$</td>
<td>3.70$^{+0.19}_{-0.18}$</td>
<td>0.451$^{+0.042}_{-0.044}$</td>
<td>1.26$^{+0.034}_{-0.034}$</td>
<td>10.12$^{+0.022}_{-0.023}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^a$The $V$-band mass-to-light ratio.
$^b$The integrated cluster mass, estimated as $\log M_{\text{tot}} = \log \frac{V}{V_\odot^3} + \log L_V$.
$^c$The integrated binding energy in ergs, defined as $E_b = -(1/2) \int_0^{R_e} 4\pi r^2 \rho(r) dr$.
$^d$The central surface mass density, estimated as $\log \Sigma_0 = \log \frac{V}{V_\odot^3} + \log L_b$.
$^e$The central volume density, estimated as $\log \rho_0 = \log \frac{V}{V_\odot^3} + \log f_0$.
$^f$The surface mass density averaged over the half-light/effective radius $R_b$, estimated as $\log \Sigma_b = \log \frac{V}{V_\odot^3} + \log I_b$.
$^g$The predicted line-of-sight velocity dispersion at the cluster centre.
$^h$The predicted central 'escape' velocity with which a star can move out from the centre of a cluster, defined as $v_{\text{esc}}^2/\sigma_0^2 = 2[(W_0 + GM_{\text{tot}}/r_0)/M_{\text{tot}}]$. The two-body relaxation time at the model-projected half-mass radius, estimated as $t_\text{esc} = (2.06 \times 10^6 \text{yr}) \ln(0.4M_{\text{tot}}/M_\odot)(M_{\text{tot}}/M_\odot R_b^{3/2}/m_\odot)$, $M_\odot$ is the average stellar mass in a cluster, assumed to be 0.5 $M_\odot$.
$^i$The model's central phase-space density, defined as $\log f_0 = \log[\rho_0/(2\pi \sigma_0^3)^{1/2}]$. 

Two globular clusters in the M81 group.
Table 11. $k$-space parameters of GC-1 and GC-2 in the M81 group.

<table>
<thead>
<tr>
<th>ID</th>
<th>Detector</th>
<th>Band</th>
<th>Model</th>
<th>$\kappa_{m,1}$</th>
<th>$\kappa_{m,2}$</th>
<th>$\kappa_{m,3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>GC-1</td>
<td>ACS/WFC</td>
<td>K66</td>
<td></td>
<td>$-0.487^{+0.149}_{-0.161}$</td>
<td>$4.535^{+0.368}_{-0.249}$</td>
<td>$0.112^{+0.095}_{-0.110}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>W</td>
<td></td>
<td>$-0.305^{+0.122}_{-0.142}$</td>
<td>$4.395^{+0.263}_{-0.297}$</td>
<td>$0.197^{+0.072}_{-0.083}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S</td>
<td></td>
<td>$-1.442^{+0.166}_{-0.183}$</td>
<td>$4.096^{+0.266}_{-0.216}$</td>
<td>$-0.677^{+0.086}_{-0.104}$</td>
</tr>
<tr>
<td>GC-2</td>
<td>WFC3/UVIS</td>
<td>K66</td>
<td></td>
<td>$-0.525^{+0.139}_{-0.156}$</td>
<td>$4.524^{+0.355}_{-0.243}$</td>
<td>$0.080^{+0.086}_{-0.106}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>W</td>
<td></td>
<td>$-0.301^{+0.184}_{-0.160}$</td>
<td>$4.384^{+0.449}_{-0.354}$</td>
<td>$0.200^{+0.124}_{-0.098}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S</td>
<td></td>
<td>$-1.426^{+0.177}_{-0.188}$</td>
<td>$4.120^{+0.243}_{-0.196}$</td>
<td>$-0.663^{+0.095}_{-0.108}$</td>
</tr>
<tr>
<td>GC-2</td>
<td>WFC3/UVIS</td>
<td>K66</td>
<td></td>
<td>$0.055^{+0.086}_{-0.080}$</td>
<td>$4.654^{+0.167}_{-0.157}$</td>
<td>$0.247^{+0.048}_{-0.038}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>W</td>
<td></td>
<td>$0.193^{+0.091}_{-0.122}$</td>
<td>$4.476^{+0.179}_{-0.234}$</td>
<td>$0.310^{+0.048}_{-0.069}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S</td>
<td></td>
<td>$-0.797^{+0.125}_{-0.136}$</td>
<td>$4.214^{+0.189}_{-0.177}$</td>
<td>$-0.440^{+0.055}_{-0.085}$</td>
</tr>
<tr>
<td>GC-2</td>
<td>WFC3/UVIS</td>
<td>K66</td>
<td></td>
<td>$0.061^{+0.100}_{-0.081}$</td>
<td>$4.754^{+0.214}_{-0.140}$</td>
<td>$0.252^{+0.040}_{-0.040}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>W</td>
<td></td>
<td>$0.164^{+0.083}_{-0.085}$</td>
<td>$4.676^{+0.153}_{-0.122}$</td>
<td>$0.286^{+0.041}_{-0.036}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S</td>
<td></td>
<td>$-0.798^{+0.127}_{-0.134}$</td>
<td>$4.217^{+0.190}_{-0.180}$</td>
<td>$-0.441^{+0.056}_{-0.064}$</td>
</tr>
</tbody>
</table>

Figure 7. Comparison of structural parameters for model fits to the sample clusters observed in both F606W and F814W bands. From top to bottom: projected half-light radius and ratio of half-light to core radius. Open circles: King (1966) model; squares: Sérsic (1968) model; stars: Wilson (1975) model.

(1968) model fits to both GC-1 and GC-2. Barmby et al. (2007) presented that the agreement is better for the King (1966) model fits than the Wilson (1975) and Sérsic (1968) model fits to the M31 star clusters. The results of Ma (2015) for the M33 star clusters are in agreement with those presented by Barmby et al. (2007) for the M31 star clusters. However, we want to mention that there are only two sample star clusters here. The conclusion obtained here may not be correct for the M81 group star clusters.

5.5 Comparison of model fittings

In order to clearly present the quality of fit for different models, we show the relative quality of fit, $\Delta$, for the Wilson- and Sérsic-model fits (filled and open circles, respectively, in all panels) versus the $\kappa$-space parameters of GC-1 and GC-2 observed in the F606W band in Fig. 8. $\Delta$ is defined as

$$\Delta = \frac{\chi^2_{\text{alternate}} - \chi^2_{\text{K66}}}{\chi^2_{\text{alternate}} + \chi^2_{\text{K66}}}$$

for comparing the $\chi^2$ of the best fit of an ‘alternate’ model with the $\chi^2$ of the best fit of the King model (see Barmby et al. 2007; Mclaughlin et al. 2008, for details). If the parameter $\Delta$ is zero, the two models fit the same cluster equally well. Positive values indicate a better fit of the King model, and negative values indicate that the ‘alternate’ model is a better fit than the King model.

The $\Delta$ values are plotted as a function of some structural parameters, including the half-light radius $R_h$, total model luminosity $L_{mod}$, and the intrinsic average surface brightness $\langle \mu_V \rangle_{h}$. Fig. 8 shows that GC-1 and GC-2 are significantly better fitted by the Wilson (1975) model than by the King (1966) or Sérsic (1968) models (GC-1 has $\Delta < -0.5$ for the Wilson-model fits and GC-2 has $\Delta \sim -0.5$ for the Wilson-model fits). In addition, the King (1966) model fits the data of GC-1 and GC-2 somewhat better than the Sérsic (1968) model. These results differ from those for the clusters in NGC 5128 (Mclaughlin et al. 2008), and in M31 (Barmby et al. 2007; Wang & Ma 2013) and M33 (Ma 2015). Mclaughlin et al. (2008) showed that for the clusters in NGC 5128, the Wilson (1975) model fits as well as or better than the King (1966) model; however, Barmby et al. (2007) and Wang & Ma (2013) showed that for most clusters in M31, the King (1966) model fits better than the Wilson (1975) model. Ma (2015) indicated that the King (1966) and Wilson (1975) models fit equally well for nearly all of the M33 sample clusters, and that the Wilson (1975) model fits the M33 sample cluster data better than the Sérsic (1968) model. San Roman et al. (2012) indicated...
that the M33 young clusters (log age < 8) are notably better fitted by the Elson–Freeman–Full model (Elson, Fall & Freeman 1987) with no radial truncation, while the M33 older clusters show no significant differences between the King (1962) and the Elson et al. (1987) fits. In addition, we want to mention that Mclaughlin & van der Marel (2005) showed that globulars and young massive clusters in the Milky Way, Magellanic Clouds and Fornax dSph are systematically better fitted by the Wilson (1975) model than by the King (1966) model, and that the Sérisc (1968) model often fits these globulars and young massive clusters about as well as the Wilson (1975) model but can be significantly worse. GC-1 and GC-2 are most luminous clusters in the local universe. For luminous clusters in M31 and NGC 5128, the results are different. For M31 clusters, Barmby et al. (2007) showed that the bright clusters \(L_{\text{mod}} > 10^5 L_\odot\) are better fitted by the King (1966) model; however, for NGC 5128 clusters, Mclaughlin et al. (2008) showed that the bright clusters are generally fitted much better by the Wilson (1975) and Sérisc (1968) models. The results of GC-1 and GC-2 are somewhat different from those of M31 and NGC 5128 clusters. In fact, Barmby et al. (2007) provided the implication that the King (1966) model is more strongly preferred for more luminous M31 clusters. They suggested that the preference for the King (1966) over the Wilson (1975) model is due to some more subtle feature of the observational data that have not yet been isolated. However, the conclusion of Mclaughlin et al. (2008) is that the haloes of GCs in NGC 5128 are generically more extended than the King (1966) model allows. For GC-1 and GC-2, we consider that they have more extended haloes than the King (1966) model allows.

6 COMPARISON TO PREVIOUS RESULTS AND DISCUSSION

Jang et al. (2012) estimated the ages and masses of GC-1 and GC-2 based on the SDSS ugriz data and on the SSP models of BC03. They reported that they derived the ages of GC-1 and GC-2 to be \(\sim 15.8\) Gyr, and the masses to be \(\sim 2.5 \times 10^6 M_\odot\) for GC-1, and \(\sim 7.08 \times 10^6 M_\odot\) for GC-2. In this paper, we accurately redetermined the ages and masses of GC-1 and GC-2, based on the improved data and sophisticated fitting methods. In particular, we used the photometric measurements of the 2MASS, which can partially break the age–metallicity degeneracy, in combination with the NVU and optical photometry; and we used the magnitudes in the \(UBVRI\) and \(JHK\) bands for reducing mass uncertainties resulting from photometric uncertainties based on only the magnitudes in one band. The ages and masses of GC-1 and GC-2 obtained by Jang et al. (2012) and in this paper show that they are old and massive star clusters in the local universe. In particular, their ages show that they are as old as the universe.

Jang et al. (2012) presented the radial surface brightness profiles of GC-1 and GC-2 in the F814W band, and they derived the core and half-light radii of GC-1 and GC-2 by fitting the photometric data by the King model and the model of Elson et al. (1987) without considering the PSF. As we know, the apparent core structures of GCs are strongly influenced by the PSF (see Barmby et al. 2007 and Mclaughlin et al. 2008 for details). So, it is needed that we redetermined the core radii of GC-1 and GC-2 considering the PSF. In addition, in order to study the properties of GC-1 and GC-2 for details in the future, the other structural and dynamical parameters should be obtained besides the core and half-light radii. So, it is also needed that we derive a wide range of structural and dynamical parameters of GC-1 and GC-2 considering the PSF (see Section 5.2 for details). The structural parameters include the central surface brightness and central potential, concentration indices, core and half-light (effective) radii and total luminosity, and the predicted relaxation time-scales and phase-space densities. From the King model fits, Jang et al. (2012) derived the core radii of GC-1 and GC-2 to be \(0.0755 \pm 0.0003\) and \(0.1269 \pm 0.0003\) arcsec, respectively. By fitting the King model (King 1966), the core radii of GC-1 and GC-2 obtained here were derived to be \(0.0316 \pm 0.002\) and \(0.0891 \pm 0.005\) arcsec, respectively, based on the radial surface brightness profiles in the F814W band. It is seen that the core radii obtained here are smaller than those of Jang et al. (2012). We argue that the difference between the core radii obtained here and those obtained by Jang et al. (2012) resulted from the PSF, i.e. Jang et al. (2012) derived this parameter without considering the PSF. In addition, by fitting the King model (King 1966), the half-light radii obtained here are \(5.45 \pm 0.22\) pc and \(9.06 \pm 0.21\) pc, respectively, based on the radial surface brightness profiles in the F814W band, which are in good agreement with those of Jang et al. (2012), who derived the half-light radii of GC-1 and GC-2 to be \(6.13 \pm 0.01\) and \(9.81 \pm 0.01\) pc, respectively. However, we should mention that the results of this paper showed that GC-1 and GC-2 are significantly better fitted by Wilson (1975) model than by King (1966) or Sérisc (1968) models. So, we use the half-radii obtained based on the fitting by Wilson (1975) model in Fig. 9.

Some authors derived the masses of the most massive Local Group clusters, such as 037–B327 \(M \sim 8.5 \times 10^6 M_\odot\) (Barmby et al. 2002) or \(M \sim 3.0 \pm 0.5 \times 10^7 M_\odot\) (Ma et al. 2006) and G1 \(M \sim (7 - 17) \times 10^6 M_\odot\) (Meylan et al. 2001) or \(M \sim (5.8 - 10.6) \times 10^6 M_\odot\) (Ma et al. 2009) in M31 and \(\omega\) Cen \(M \sim (2.9 - 5.1) \times 10^6 M_\odot\) (Meylan 2002) in the Milky Way. Martini & Ho (2004) derived the masses of the most luminous GCs in NGC 5128 to range from \(M \sim 1.0\) to \(M \sim 9.0 \times 10^6 M_\odot\). Recently, Mayya et al. (2013) derived the mass of the brightest GC in M81, GC1, to be \(M \sim 1.0 \times 10^7 M_\odot\). Comparing with these most massive GCs mentioned above, GC-1 and GC-2 are among the most massive GCs.
clusters in the local universe. In particular, GC-2 is one of the most massive clusters in the local universe. Meylan et al. (2001) argued that the very massive GCs blur the former clear (or simplistic) difference between GCs and dwarf galaxies. In fact, Zinnecker et al. (1988) had proposed that the nucleated dEs would contribute their naked nuclei as a population of GCs when they were accreted and disrupted by a larger galaxy. Martini & Ho (2004) posited that some of the massive GCs in NGC 5128 are nuclei of tidally dwarfs based on their large masses and the possible detection of ‘extratidal light’ by Harris et al. (2002) (but see McLaughlin et al. 2008 for counter-arguments for the massive GCs in NGC 5128). Based on the position of a cluster on the size–luminosity plane, Mackey & van den Bergh (2005) suggested that the most luminous Local Group clusters, such as M54 and ω Centauri in the Milky Way, G1 in M31 and the most luminous clusters in NGC 5128, are the cores of former dwarf galaxies. The large masses of GC-1 and GC-2 may make them different from the rest of the GC population in M81 and M82. Jang et al. (2012) suggested that these two massive clusters are remnants of dwarf galaxies based on the empirically established relation $r_h = 0.25 \times M_V^{-2.95}$ (Mackey & van den Bergh 2005), which forms the upper envelope of Galactic GCs in the $M_V$ versus $r_h$ plane. In Section 5.3, we see that, for both GC-1 and GC-2, the fitted King model (King 1966) falls clearly below the measured profiles at the largest radii, although the model fit was accurate at smaller radii. In fact, Harris et al. (2002) have already found this case for the most luminous GCs in NGC 5128, in which they explained that these clusters exhibit ‘extratidal light’ continuing outward past the nominal tidal radius obtained based on the King (1966) model. These authors further suggested the ‘extratidal light’ as the residual trace of the field-star population of dwarf satellite galaxies, and these most luminous GCs as the luminous compact nuclei of former dwarf satellite galaxies. The large masses and the possible detection of ‘extratidal light’ for GC-1 and GC-2 may present the further evidence that these two GCs are nuclei of tidally dwarfs as suggested by Jang et al. (2012). However, we want to mention the fact that, from Fig. 6, we can see that the Wilson (1975) model can fit the entire profiles of GC-1 and GC-2 accurately without the need to invoke amounts of ‘extratidal light’ implied by the King (1966) model fits. In fact, McLaughlin et al. (2008) argued that the ‘excess’ light implied by the King (1966) model fits to some massive clusters of NGC 5128 is not likely the signature of genuine tidal debris, but a symptom of generic shortcomings in the model itself, i.e. the theoretical basis for it is weak in the low-density and unrelaxed farthest reaches of cluster envelopes, and these authors showed that the Wilson (1975) model can fit these massive clusters of NGC 5128 accurately. The results and comments of McLaughlin et al. (2008) may imply that these massive clusters in NGC 5128 have not the residual trace of the field-star population of dwarf satellite galaxies. So, it is needed to be confirmed in the future that the massive clusters of NGC 5128 are the luminous compact nuclei of former dwarf satellite galaxies. We argued that GC-1 and GC-2 are in this case. In addition, GC-1 and GC-2 are not the most luminous clusters in M81 and M82 (see Fig. 9). Especially, nearly 20 clusters are more luminous than GC-1. So, we suggested that GC-1 is only a luminous cluster in M81 and M82; however, GC-2 may be different from conventional clusters in M81 and M82. We will discuss GC-2 in detail below. From the Wilson (1975) model fits, the half-light radii of GC-2 obtained here are 13.49 and 11.02 pc based on the radial surface brightness profiles in the F606W and F814W bands, respectively. Its large size and high luminosity ($M_V = -10.63$ mag) make GC-2 to be an ultra-compact dwarfs (UCD) in the M81 group. Fig. 9 shows the half-light radius ($r_h$) versus absolute magnitude ($M_V$) diagram, where data for GC-1 and GC-2 are plotted along with those for the GCs (good and spectroscopically confirmed) in M81 (Nantais et al. 2011) and the star clusters (older than 1 Gyr) in M82 (Lim et al. 2013), and for the UCDs from Brodie et al. (2011). In Fig. 9, we used the half-light radii of GC-1 and GC-2 obtained by fitting the radial surface brightness profiles in the F606W band by the Wilson (1975) model. Fig. 9 makes it evident that GC-2 occupies the same area of the UCDs, indicating that GC-2 is a UCD in the M81 group. It is well known that UCDs are compact stellar systems that are more luminous and larger than typical GCs, but more compact than typical dwarf galaxies. They were originally discovered independently by Hilker, Infante & Richtler (1999) and Drinkwater et al. (2000) in spectroscopic surveys of the centre of the Fornax cluster, and they have sizes of $10 < r_h < 100$ pc and luminosities of $M_V < -9$ mag (Liu et al. 2015). Although UCDs have so far been found mostly in dense environments, at the centres of galaxy clusters, or near massive galaxies, they have also been discovered in galaxy groups and even relatively isolated galaxies (see Zhang et al. 2015, for a review). Evstigneeva et al. (2007) discovered one definite and four possible UCD candidates in a photometric search in six galaxy groups. All of these UCDs are intergalactic and not associated with any particular galaxy. Especially, the UCD in the Dorado Group (Evstigneeva et al. 2007) is an intragroup object like GC-2 in the M81 group. As mentioned above, Jang et al. (2012) considered GC-2 to be a remnant of a dwarf galaxy based on the distribution in the $M_V$ versus $r_h$ plane, which accreted to M81 and is receding now. Till now, there has been ongoing debate about the origin of UCDs. A number of different origins of UCDs were brought up: (1) they are merely luminous, genuine GCs (Mieske, Hilker & Infante 2002; Murray 2009); (2) they are the products of the merger of super star clusters (Fellhauer & Kroupa 2002; Bekki et al. 2004); (3) they are the stripped nuclei of dEs (Bekki, Couch & Drinkwater 2001; Bekki et al. 2003; Goerdt et al. 2008); (4) they are remnants of primordial compact galaxies (Drinkwater et al. 2004). Brodie et al. (2011) presented that the M87 UCDs are predominantly stripped nuclei. At the same time, these authors consider it more probable that UCDs have their origins as nuclei that have since been stripped by tidal forces. However, Mieske, Hilker & Infante (2004), Mieske et al. (2006) and Mieske, Hilker & Misgeld (2012) presented that the luminosity and size distribution of UCDs show a smooth transition to the regime of GCs. So, these authors suggested that, from a statistical point of view, there is no need to invoke an additional formation channel based on the conclusion that the number counts of UCDs are fully consistent with them being the bright tail of the GC population. In addition, Hasegan et al. (2005) and Mieske et al. (2008) presented that the most massive UCDs show evidence for higher dynamical mass-to-light ratios than those derived from stellar population modelling alone, suggesting that some massive UCDs host a large amount of dark matter (see also Pandya, Mulchaey & Greene 2016). For one UCD (M60-UCD1), it has been shown that a massive black hole is responsible for the elevated mass-to-light ratio (Seth et al. 2014). Especially, Mieske et al. (2013) presented two UCD formation channels: one is a ‘globular cluster channel’ which is important mainly for UCDs with $M \lesssim 10^7 M_\odot$ and another is tidal transformation of massive progenitor galaxies which dominates for UCDs with $M \gtrsim 10^7 M_\odot$ and still contributes for lower UCD masses. It is unfortunate that we cannot derive the spectroscopically observed velocity dispersion of GC-2 in this paper, i.e. we cannot derive the dynamical mass of GC-2. In addition, it is true that the mass of GC-2 is smaller than $10^7 M_\odot$. So, we cannot give a clear conclusion of the origin of GC-2 here.
7 SUMMARY

In this paper, we study the two GCs in the remote halo of M81 and M82 in the M81 group: GC-1 and GC-2.

(1) We derive the magnitudes in intermediate-band filters of the BATC system.

(2) We determine these two cluster’s ages and masses by comparing their SEDs (from 2267 to 20,000 Å, comprising photometric data in the near-ultraviolet of GALEX, 14 BATC intermediate-band and 2MASS NIR JHK filters) with theoretical stellar population-synthesis models.

(3) The ages of GC-1 and GC-2 obtained in this paper are 15.50 ± 3.20 for GC-1 and 15.10 ± 2.70 Gyr, respectively, which showed that they are old objects in the M81 group.

(4) The masses of GC-1 and GC-2 obtained in this paper are 1.77–2.04 × 10^6 M⊙, respectively, which showed that they are among most massive clusters in the local universe, especially GC-2 is one of the most massive clusters in the local universe.

(5) We derived the structural and dynamical parameters of GC-1 and GC-2 based on the HST images from fitting the surface brightness profiles to three different models combined with the mass-to-light ratios (M/L values) from population-synthesis models.

(6) Catalogues of fundamental structural and dynamical parameters obtained here are parallel in form to the catalogues produced by McLaughlin & van der Marel (2005) for the GCs and massive young star clusters in the Milky Way, Magellanic Clouds, and the Fornax dwarf spheroidal, by Barmby et al. (2007) and Wang & Ma (2013) for the M31 star clusters, by Ma (2015) for the M33 star clusters, and by McLaughlin et al. (2008) for the NGC 5128 star clusters.

(7) For the first time, we conclude that GC-2 is a UCD in the M81 group based on the r0 versus M∗ diagram.

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We would like to thank Dr. McLaughlin for his help in finishing this paper. He provided us a table including some parameters which were model-dependent function of W0 or c. We are indebted to the referee for his/her thoughtful comments and insightful suggestions that improved this paper greatly. This study has been supported by the National Natural Science Foundation of China (NSFC, No. 11373035) and by the National Basic Research Program of China (973 Program, Nos. 2014CB845704 and 2013CB834902) and by the National Natural Science Foundation of China (NSFC, Nos. 11603035, 11373033, 11433005, 11673027 and 11603034).

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**SUPPORTING INFORMATION**

Supplementary data are available at MNRAS online.

**Table 6.** Intensity profiles for GC-1 and GC-2 in the M81 group.

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