AN UPDATED CATALOG OF M31 GLOBULAR-LIKE CLUSTERS: UBVRI PHOTOMETRY, AGES, AND MASSES

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ABSTRACT

We present an updated UBVRI photometric catalog containing 970 objects in the field of M31, selected from the Revised Bologna Catalog (RBC v.4.0), including 965, 967, 956, 953, and 827 sources in the individual UBVRI bands, respectively, of which 205, 123, 14, 126, and 109 objects do not have previously published photometry. Photometry is performed using archival images from the Local Group Galaxies Survey, which covers 2.2 deg² along the major axis of M31. Detailed comparisons show that our photometry is fully consistent with previous measurements in all filters. We focus on 445 confirmed “globular-like” clusters and candidates, comprising typical globular and young massive clusters. The ages and masses of these objects are derived by comparing their observed spectral-energy distributions with simple stellar population synthesis. Approximately half of the clusters are younger than 2 Gyr, suggesting that there has been significant recent active star formation in M31, which is consistent with previous results. We note that clusters in the halo (r_projected > 30 kpc) are composed of two different components: older clusters with ages > 10 Gyr and younger clusters with ages around 1 Gyr. The spatial distributions show that the young clusters (< 2 Gyr) are spatially coincident with the galaxy’s disk, including the “10 kpc ring,” the “outer ring,” and the halo of M31, while the old clusters (> 2 Gyr) are spatially correlated with the bulge and halo. We also estimate the masses of the 445 confirmed clusters and candidates in M31 and find that our estimates agree well with previously published values. We find that none of the young disk clusters can survive the inevitable encounters with giant molecular clouds in the galaxy’s disk and that they will eventually be disrupted on timescales of a few Gyr. Specifically, young disk clusters with a mass of 10^4 M☉ are expected to dissolve within 3.0 Gyr and will, thus, not evolve to become globular clusters.

Key words: catalogs – galaxies: individual (M31) – galaxies: star clusters: general – globular clusters: general

Online-only material: machine-readable tables

1. INTRODUCTION

Star clusters comprise an important stellar population component of galaxies and their age distributions trace the main events in the formation and evolution of their host galaxies. For a long time, star clusters were thought of as members of two distinct types, specifically open and globular clusters (OCs and GCs, respectively). OCs are young, not very massive, faint, diffuse, and usually located in galactic disks, quite contrary to GCs, which are old, massive, luminous, centrally concentrated, and usually located in the halos of their host galaxies. However, this simplistic picture has been changing since the discovery of young massive star clusters (YMCs) in many galaxies, including the Milky Way (Ascenso et al. 2007a, 2007b), M31 (Barmby et al. 2009; Ma et al. 2009; Caldwell et al. 2009; Perina 2009; Perina et al. 2010; Hodge et al. 2010), M82 (McCready 2009), and NGC 1140 (Moll et al. 2008). YMC properties span those of both OCs and GCs, with typical masses (> 10^3 M☉) greater than those of (most) OCs and young ages (< 1 Gyr) quite different from present-day GCs, so that they are often considered candidate proto-GCs. The new category of YMCs renders cluster classification blurred and difficult. In this paper, we use the term “globular-like cluster” to distinguish massive (YMCs and GCs) from less massive clusters (OCs). Since OCs are usually faint and located in galactic disks, which make them difficult to study, we focus on “globular-like clusters.”

Located at a distance of ~780 kpc (Stanek & Garnavich 1998; Macri 2001; McConnell & Mcconnachie et al. 2005), M31 (also known as the Andromeda galaxy) is the nearest large spiral galaxy in our Local Group of galaxies. Therefore, it constitutes an ideal laboratory for studies of star clusters in external galaxies. Based on Hubble Space Telescope (HST) Wide Field and Planetary Camera-2 (WFPC2) images, Krienke & Hodge (2007) suggested that there may be ~80,000 star clusters in the M31 disk. Most of these disk clusters are faint OCs. The number of GCs in M31 is much smaller. Barmby & Huchra (2001) estimated their total number at 460 ± 70, while Perina et al. (2010) arrived at ~530, with an additional ~100 YMCs. To limit the scope of this paper, we will focus on the GCs and YMCs in M31. Since GCs and YMCs are luminous, they are relatively easy to observe and study. Studies aimed at identification, classification, and analysis of the population of M31 globular-like clusters have been undertaken since the pioneering work of Hubble (1932; see, e.g., Vetesiők 1962; Sargent et al. 1977; Battistini et al. 1980, 1987, 1993; Crampton et al. 1985; Barmby et al. 2000). These studies have provided a large amount of photometric data in different photometric systems, including photographic plates, as well as CCD, photoelectric, and even visual photometry.

Mackey et al. (2006) reported the discovery of eight remote GCs in the outer halo of M31 based on deep HST/Advanced Camera for Surveys images. Kim et al. (2007) found 1164 GCs and GC candidates in M31 using the Kitt Peak National Observatory’s (KPNO) 0.9 m and the WIYN (Wisconsin, Indiana, Yale, and the National Optical Astronomical Observatories) 3.5 m telescopes, of which 559 and 605 were previously known GCs and newly identified GC candidates, respectively. Huxor et al. (2008) detected 40 new GCs in the M31 halo based on Isaac Newton Telescope and Canada–France–Hawaii Telescope data. Caldwell et al. (2009) published a new catalog of 670 likely star
clusters, stars, possible stars, and galaxies in the field of M31, all with updated high-quality coordinates accurate to 0\'\'.2, based on images from either the Local Group Galaxies Survey (LGGS; Massey et al. 2006) or the Digitized Sky Survey (DSS). Recently, Peacock et al. (2010) identified M31 clusters using images from the UK Infrared Telescope’s Wide Field Camera (WFCAM) and the Sloan Digital Sky Survey (SDSS) archives, and obtained photometry in the SDSS ugriz and the near-infrared (NIR) K bands. In addition, the authors combined all identifications and photometry of M31 star clusters from the literature with their new sample. Their updated M31 star cluster catalog includes 416 old, confirmed clusters, 156 young clusters, and 373 candidate clusters. Very recently, Hodge et al. (2010) discovered 77 new star clusters in star-forming regions based on HST/WFPC2 observations. The latest and most comprehensive M31 GC catalog—the Revised Bologna Catalog of M31 globular clusters and candidates (RBC v.4.04; Galletti et al. 2004, 2006, 2007, 2009)—contains 2045 objects in M31, including 663 confirmed star clusters, 604 cluster candidates, and 778 other objects initially thought to be GCs but later proved to be stars, asterisms, galaxies, and HII regions. The authors adopted the photometry of Barmby et al. (2000) as their reference and transformed other measurements to homogenize the final photometry database. In fact, some confirmed GCs in the RBC are probably YMCs. The updated RBC also includes the most recently discovered star clusters and photometry from Mackey et al. (2006), Kim et al. (2007), Huxor et al. (2008), and Caldwell et al. (2009).

The \( \chi^2 \) minimization technique used for estimating ages, metallicities, reddening values, and masses of extragalactic star clusters has been described in detail by, e.g., Jiang et al. (2003), Peacock et al. (2005a), Fan et al. (2006), Ma et al. (2007, 2009), and Wang et al. (2010). Jiang et al. (2003) presented Beijing–Arizona–Taiwan–Connecticut (BATC) photometry of 172 GCs in the central \( \sim 1 \) deg\(^2\) region of M31 and estimated their ages using simple stellar population (SSP) models. de Grijs et al. (2005a) fitted the ages of Large Magellanic Cloud star clusters based on broadband spectral-energy distribution (SED) fits. Fan et al. (2006) estimated the ages of 91 GCs in M31 by matching BATC intermediate-band and Two Micron All Sky Survey (2MASS) \( JHK \) SEDs with Bruzual & Charlot (2003, hereafter BC03) SSP models. Ma et al. (2007) determined the ages of an old M31 GC (S312) based on GALEX near-ultraviolet, optical broadband, 2MASS \( JHK \), and BATC photometry. Subsequently, Ma et al. (2009) fitted the ages of 35 GCs in the central M31 field that were not included in Jiang et al. (2003) based on BATC, 2MASS \( JHK \), and GALEX data, combined with the GALEV SSP models. Very recently, Wang et al. (2010) performed photometry for another 104 M31 GCs with BATC multicolor observations and estimated the ages by fitting their SEDs with GALEV SSP models, revealing the presence of young, intermediate-age, and old cluster populations in M31.

In this paper, we first perform aperture photometry of 970 RBC objects based on images from the LGGS. Using photometry in the \( UBVRI \) bands and \( JHK \) magnitudes from the RBC, the ages and masses of the confirmed clusters in our sample are estimated by comparing the observed SEDs with BC03 SSP synthesis models. This paper is organized as follows. Section 2 describes the sample selection and \( UBVRI \) photometry. In Section 3.1, we describe the SSP models used as well as our method to estimate the cluster ages. In Section 3.2, we present the clusters’ mass estimates, and we summarize and conclude the paper in Section 4.

\[ \chi^2 = \frac{(D - f)\sigma^2}{2} \]

Available from http://www.bo.astro.it/M31.

2. DATA

2.1. Sample

We selected our sample clusters from the RBC v.4.0, which is a compilation of photometry and identifications from many previous catalogs. We used archival \( UBVRI \) images from the LGGS, which covers a region of 2.2 deg\(^2\) along the galaxy’s major axis. The images we used consisted of 10 separate but overlapping fields with a scale from 0\'\'261 pixel\(^{-1}\) at the center to 0\'\'258 pixel\(^{-1}\) in the corners of each image. The field of view of each mosaic image is \( 36' \times 36' \). The observations were taken from 2000 August to 2002 September with the KPNO 4 m telescope. The median seeing of the LGGS images is \( \sim 1'\). Caldwell et al. (2009) inspected the images and found some new clusters, including over 100 young clusters. To limit the scope of our work, we only perform photometry of the clusters in the LGGS images using the identifications provided by Caldwell et al. (2009). We employed IRAF/DAOFIND to find the sources in the images and match them to the RBC coordinates. We matched 1191 objects in all LGGS fields in the \( V \) band. To prevent mistakes, we checked each object visually in the images. Like Caldwell et al. (2009), we also ran into positional errors for five objects (NB18, B353, NB60, V229, and NB57) in the RBC v.4.0; these five sources were not detected at the RBC coordinates in the LGGS images. In addition, 138 clusters listed in the RBC v.4.0 are actually composed of two or more individual stars in the images. Another 5 objects (BH18, B088D, B091D, C011, and B117) have very bright stars nearby, causing contamination. 32 are saturated, 10 are too faint to be detected, 18 have very strong background gradients and 1 nebula (SK150C), 4 (SK156B, SK099A, SK062B, and SK105B) have very high backgrounds, and 8 are suspected to be galaxies. In total, we excluded those 221 objects to make our sample as clean as possible. Eventually, we detected 970 RBC objects (including all object types) in the LGGS survey images for which we will perform photometry in this paper. Figure 1 shows the spatial distribution of the 970 objects in the LGGS fields. Confirmed GCs are marked with circles, GC candidates are denoted as triangles, while other objects are indicated by pluses. The large ellipse is the \( D_{25} \) boundary of the M31 disk (Racine 1991), while the two small ellipses are the \( D_{25} \) boundaries of NGC 205 (northwest) and M32 (southeast). The 10 large squares are the LGGS field boundaries. We will mainly focus on the confirmed and candidate globular-like clusters (\( f = 1 \) and 2 in the RBC v.4.0, respectively), since we anticipate the presence of a significant fraction of YMCs in this sample.

2.2. Integrated Photometry

We used the LGGS archival images of M31 in the \( UBVRI \) bands to perform photometry. Previously, Massey et al. (2006) compiled point-spread function (PSF) photometry for 371,718 stars (point sources) in the M31 fields, with photometric uncertainties of <10% below \( V = 23 \) mag. However, there is as yet no published LGGS photometry for extended sources, such as star clusters and galaxies. Recently, Caldwell et al. (2009) undertook aperture photometry of the resolved star clusters only in the \( V \) band and studied the nature of over 100 young M31 clusters. However, LGGS photometry of M31 clusters in the other bands (\( BVRI \)) has not yet been compiled.

For this reason, we perform aperture photometry of the M31 clusters found in the LGGS images in all of the \( UBVRI \) bands to provide a comprehensive and homogeneous photometric
the two small ellipses are the IRAF catalog of M31 globular-like clusters. The photometry routine candidates are denoted as triangles, while other objects are indicated by pluses.

Spatial distribution of the 970 objects selected from the RBC v.4.0

Table 1

| Object | $U$ (mag) | $B$ (mag) | $V$ (mag) | $R$ (mag) | $I$ (mag) | $r_{ap}$ (″)
|--------|-----------|-----------|-----------|-----------|-----------|-----------
| B001   | 18.783 ± 0.009 | 18.261 ± 0.008 | 17.156 ± 0.004 | 16.455 ± 0.003 | 15.712 ± 0.002 | 2.90 |
| B005   | 16.880 ± 0.004 | 16.552 ± 0.004 | 15.529 ± 0.002 | 14.895 ± 0.002 | ... | 5.13 |
| B015   | 20.344 ± 0.023 | 19.411 ± 0.013 | 18.130 ± 0.007 | 17.265 ± 0.005 | 16.381 ± 0.004 | 2.19 |
| B017   | 17.547 ± 0.004 | 17.048 ± 0.004 | 15.968 ± 0.002 | 15.246 ± 0.002 | ... | 3.86 |
| B018   | 18.614 ± 0.010 | 18.372 ± 0.010 | 17.517 ± 0.007 | 16.961 ± 0.006 | 16.351 ± 0.007 | 3.86 |
| B021   | 19.301 ± 0.015 | 18.764 ± 0.012 | 17.650 ± 0.009 | 16.904 ± 0.007 | 16.048 ± 0.005 | 3.86 |
| B025   | 17.959 ± 0.005 | 17.702 ± 0.006 | 16.799 ± 0.004 | 16.205 ± 0.004 | ... | 2.90 |
| B027   | 16.669 ± 0.003 | 16.486 ± 0.003 | 15.642 ± 0.002 | 15.104 ± 0.002 | ... | 3.86 |
| B028   | 17.824 ± 0.005 | 17.726 ± 0.006 | 16.929 ± 0.004 | 16.409 ± 0.004 | 15.863 ± 0.004 | 2.90 |
| B029   | 18.297 ± 0.007 | 17.725 ± 0.006 | 16.713 ± 0.004 | 16.069 ± 0.004 | 15.380 ± 0.004 | 3.86 |

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

Figure 1. Spatial distribution of the 970 objects selected from the RBC v.4.0 and their loci in the LGGS fields. Confirmed GCs are marked with circles, GC candidates are denoted as triangles, while other objects are indicated by pluses. The large ellipse is the $D_{25}$ boundary of the M31 disk (Racine 1991), while the two small ellipses are the $D_{25}$ contours of NGC 205 (northwest) and M32 (southeast). The 10 large squares are the LGGS fields.

catalog of M31 globular-like clusters. The photometry routine we used is IRAF/DAOPHOT (Stetson 1987). Following Caldwell et al. (2009), we use eight different aperture sizes (with radii of $r_{ap} = 1″03, 1″64, 2″19, 2″90, 3″86, 5″13, 6″82, and 9″06) to ensure that we adopt the most appropriate photometric radius that includes all light from the objects, but excludes as much as possible and to the extent that this was obvious) extraneous field stars. We decided on the size of the aperture needed for the photometry based on visual examination. The local sky background was measured in an annulus with an inner radius of 9″29 and a width of 2″58. (Although we performed our cluster photometry using different apertures, we chose to use identical background annuli for convenience. We tested the validity of this approach for one source based on using different apertures and different backgrounds, including background gradients. The results show that background variations result in uncertainties at a level of only ~0.001 mag.) To check whether and how seriously aperture variations affect our results, we performed tests with a series of different apertures, ranging from the proper radius given in Table 1 to a radius of 10″ larger than the tabulated value. As a result, the magnitudes typically only vary by ~0.06 mag due to background variations and contamination from other sources. The instrumental magnitudes were then calibrated to the standard Johnson–Kron–Cousins $UBVRI$ system by comparing the published magnitudes of stars from Massey et al. (2006), who calibrated their photometry with standard stars of Landolt (1992), with our instrumental magnitudes. Since the magnitudes in Massey et al. (2006) are given in the Vega system, our photometry is also tied to that system. Finally, we obtained photometry for 970 objects, with 965, 967, 965, 953, and 827 sources in the individual $UBVRI$ bands, respectively. After matching our photometry with the measurements in the RBC v.4.0, Barmby et al. (2000), and Peacock et al. (2010), we found that 205, 123, 14, 126, and 109 objects (in the corresponding passbands) do not have any previously published photometry. We remind the reader that the photometry of Peacock et al. (2010) is in the $ugriz$ system, which we transferred to the Johnson–Kron–Cousins $UBVRI$ system based on Jester et al. (2005). (Their equations were derived for a sample of stars with $K - I < 1.15$ mag.) Table 1 lists our new $UBVRI$ magnitudes and the aperture used. The table only includes photometry for objects that are located in the LGGS images, with errors given by IRAF/DAOPHOT. The object names follow the naming convention of Barmby et al. (2000), Perrett et al. (2002), and Galletti et al. (2004, 2006, 2007).

Since we used the same images as Caldwell et al. (2009), a direct comparison can tell us whether or not our photometry is reliable. However, Caldwell et al. (2009) only include photometry in the $V$ band. Figure 2 shows comparisons of the $V$-band photometry and apertures. We note that in the left-hand panel, the $V$-band magnitudes are very consistent. In the right-hand panel, we use the point size to represent the frequency of the aperture used. It is clear that for small apertures the two methods are reasonably consistent. However, for larger apertures, our aperture are a few arcseconds smaller than Caldwell et al.’s (2009). In fact, the aperture of every source considered here was determined by visual checks to make sure that it was large enough, but not too large (to avoid contamination from other...
sources). The left-hand panel proves that, with a small number of exceptions, the choice of aperture does not significantly affect the resulting photometry.

To examine the quality and reliability of our photometry, we show comparisons of the aperture magnitudes of the 970 objects considered here with the magnitudes collected from various sources in the RBC v.4.0 in Figure 3. We find good agreement in all bands, with an rms scatter in the photometric differences (throughout this paper defined in the sense of our determination minus literature measurement) ranging from $\sigma = 0.325$ mag in the $I$ band (590 objects) to $\sigma = 0.398$ in the $U$ band (586 objects). This is in spite of the fact that no effort was made to ensure that the apertures used in both data sets were the same. The photometric offsets (defined as $\sigma/\sqrt{N}$, where $\sigma$ is the standard deviation and $N$ is the number of data points) and the rms scatter of the differences between the RBC v4.0 set and our new magnitudes are summarized in Table 2, showing no apparent systematic uncertainties. (The offsets are $\sim 0.1 \sigma$–$0.2 \sigma$.

In the $U$ and $BVRI$ filters, our photometry is brighter and fainter, respectively, at these levels than the RBC v.4.0 compilation.)

We also compare our photometry with previous measurements from Barmby et al. (2000), which were based on one photometric system and much more homogeneous in nature than the RBC v.4.0 data. Figure 4 shows the comparison. The

Table 2

| Band | Mean Offset | $\sigma$ | Number |
|------|-------------|---------|--------|
| $U$  | $-0.024 \pm 0.016$ | 0.398   | 586    |
| $B$  | $0.088 \pm 0.015$   | 0.373   | 651    |
| $V$  | $0.058 \pm 0.011$   | 0.346   | 946    |
| $R$  | $0.083 \pm 0.014$   | 0.353   | 606    |
| $I$  | $0.049 \pm 0.013$   | 0.325   | 590    |

Note. Offset = our measurement – literature value.
photometric offsets and rms scatter of the differences between their and our magnitudes are summarized in Table 3.

We also compared our photometry with previous measurements from Peacock et al. (2010), whose photometry is based on the RBC v.4.0 data. As discussed in Section 2.2, we transferred the SDSS $ugriz$ system to the standard broadband system and show the comparison in Figure 5. As for Table 3, the photometric offsets and rms scatter of the differences between their and our magnitudes are summarized in Table 4.

Figure 6 shows the distributions of the $UBVRI$ magnitudes of the M31 star clusters from Table 1. The black filled histograms contain the full sample of confirmed, globular-like star clusters ($f = 1$ in the RBC) and candidates ($f = 2$), while the gray filled histograms include only the confirmed globular-like clusters. The cluster candidates are mostly found near the faint ends of the distributions, as expected. The peaks of the distributions in all bands agree well with those of the confirmed M31 GCs reported by Galleti et al. (2006) and Fan et al. (2009), suggesting that our selection of confirmed, globular-like star clusters is not systematically biased.

### Table 3

| Band | Mean Offset | $\sigma$ | Number |
|------|-------------|---------|--------|
| $U$  | $0.012 \pm 0.018$ | 0.196  | 124    |
| $B$  | $0.010 \pm 0.015$ | 0.201  | 184    |
| $V$  | $0.013 \pm 0.014$ | 0.194  | 198    |
| $R$  | $0.018 \pm 0.013$ | 0.177  | 174    |
| $I$  | $0.088 \pm 0.022$ | 0.262  | 139    |

Note. Offset = our measurement $-$ literature value.

### 3. RESULTS AND ANALYSIS

In this section, we describe the methods and processes used for the determination of the cluster ages and masses based on SED fitting. We supplemented our photometry (Table 1) with RBC v.4.0 measurements if we could not obtain the relevant measurements ourselves from the LGGS images. This should not introduce any additional systematic effects, given the absence of large systematic offsets (>0.1 mag) in Figures 3, 4, and 5. Our final working sample is composed of 445 confirmed globular-like clusters and candidates. It is important to keep in mind that the sample also includes a small number of clusters with photometry completely taken from the literature. Our aim in this selection procedure is to base our results on the largest possible cluster sample.

#### 3.1. Ages of the Globular-like Clusters

From an observational point of view, studying M31 star clusters is complicated, since in most cases we only have access to their integrated spectra and photometry and cannot study the resolved stellar populations. Therefore, we can only obtain their key physical parameters, such as ages and metallicities, by careful analysis of the integrated observables. However, a large body of evidence suggests that a strong age–metallicity degeneracy dominates if only optical photometry is used (Worthey 1994; Arimoto 1996; Kaviraj et al. 2007). Anders et al. (2004b) studied the star clusters in NGC 1569 using multiwavelength HST observations. They strongly recommend to use NIR photometry as the only way to break the degeneracy for young clusters (see also de Jong 1996). Anders et al. (2004a) investigated the systematic uncertainties inherent to SED fits in the $UBVRIJH$ bands based on stellar population synthesis modeling and found that access to at least one NIR passband can significantly improve the results and constrain the metallicity. They concluded that the degeneracy can be partially broken by adding NIR photometry to the optical colors, depending on the age of the stellar population. de Grijs et al. (2005a) showed that the use of NIR colors can greatly contribute to break the age–metallicity and age–extinction degeneracies. Thus, in our fits, we will combine our $UBVRI$ photometry with $JHK$ photometry from the RBC v.4.0 to disentangle the degeneracies and obtain more accurate results.

The RBC contains 703 confirmed clusters or candidates in M31 GCs that have homogeneous NIR $JHK$ data, of which 5 We obtained photometry for 970 objects from the LGGS images, which we combined with RBC v.4.0 magnitudes (2045 objects) to compile the largest possible photometric sample. We selected the $f = 1$ and 2 clusters with photometry in no fewer than six of the eight available filters ($UBVRIJHK$) for our age determinations, yielding 445 objects. A large number of these 445 clusters are located in the galaxy’s halo (see Figures 14 and 15) and not covered by the LGGS images (see Figure 1). For most of these halo clusters, the photometry was therefore completely obtained from the RBC.
the majority were obtained from 2MASS photometry by Galleti et al. (2004) and only 17 are from previously published data. For point sources the authors use \( r = 4 \) arcsec, while for extended sources they use \( r = 5 \) arcsec. Further, Galleti et al. (2004) show that their 2MASS photometry is quite consistent with pre-2MASS photometry. As for the NIR JHK magnitudes, the uncertainties in the fitting routines are estimated as in Fan et al. (2006) by applying the relations in Figure 2 of Carpenter et al. (2001), which shows the observed magnitude uncertainty as a function of magnitude for bright stars in the 2MASS JHK bands.

We use a \( \chi^2 \) minimization technique for our age estimates, comparing the observed integrated SEDs with theoretical SSP models. We take advantage of the BC03 SSP models, using Padova 1994 evolutionary tracks and a Chabrier (2003) initial mass function (IMF) with lower and upper mass cutoffs of 0.1 and 100 \( M_\odot \), respectively. The BC03 SSP synthesis models include six initial metallicities, \( Z = 0.0001, 0.0004, 0.004, 0.008, 0.02 \) (solar), and 0.05, with 221 unequally spaced time steps from 0 to 20 Gyr. Following Fan et al. (2006), Ma et al. (2007, 2009), and Wang et al. (2010), but improving on their approaches, a new, higher-resolution spectral grid containing 100 metallicities (from \( Z = 0.0001 \) to 0.05) was created by interpolating in logarithmic space, with equally spaced intervals of \( \log Z \) between the newly created templates.

The BC03 SSP model spectra can be easily convolved to magnitudes in the AB system using the filter-response functions in the \( UBVRIJK \) bands. The apparent magnitudes of the BC03 SSP synthesis models in the AB system are given by

\[
m_{\text{AB}}(t) = -2.5 \log \left[ \frac{\int_{\lambda_1}^{\lambda_2} d\lambda \lambda F_\lambda(\lambda, t) R(\lambda)}{\int_{\lambda_1}^{\lambda_2} d\lambda \lambda R(\lambda)} \right] - 48.60, \tag{1}
\]

where \( R(\lambda) \) is the filter-response function and \( F_\lambda(\lambda, t) \) is the flux, which is a function of wavelength (\( \lambda \)) and evolutionary time (\( t \)). \( \lambda_1 \) and \( \lambda_2 \) are the lower and upper wavelength cutoffs of the respective filter (see BC03).

Since all our photometric measurements (\( UBVRIJK \), both our own photometry and that from the RBC) are calibrated in the Vega system, for convenience of comparison we need to convert the observed integrated magnitudes to the AB system using the Kurucz (1992) SEDs.

For those clusters in our sample that have available reddening values from Fan et al. (2008) or Barmby et al. (2000), the magnitudes were corrected for reddening assuming a Cardelli et al. (1989) extinction curve, so that their ages (\( t \)) can be determined by comparing the interpolated high-resolution BC03 SSP synthesis models with the SEDs from our photometry and with \( Z \) as a free parameter, i.e.,

\[
\chi^2_{\text{min}}(t, Z) = \min \left[ \sum_{i=1}^{8} \left( \frac{m_{\text{obs}}^{i} - m_{\text{mod}}^{i}}{\sigma_i} \right)^2 \right], \tag{2}
\]

where \( m_{\text{mod}}^{i}(t, Z) \) is the integrated magnitude in the \( i \)th filter in a theoretical SSP at age \( t \) and for metallicity \( Z \), \( m_{\text{obs}}^{i} \) represents the observed, integrated magnitude in the same filter, \( m_{\lambda_i} = UBVRIJK \), and

\[
\sigma_i^2 = \sigma_{\text{obs},i}^2 + \sigma_{\text{mod},i}^2. \tag{3}
\]

Here, \( \sigma_{\text{obs},i} \) is the observational uncertainty. Since the RBC does not include any magnitude uncertainties, we applied the rough estimates from Galleti et al. (2004), i.e., 0.05 and 0.08 mag for the \( BVRI \) and \( U \) bands, respectively. As for the NIR \( JHK \) magnitudes, the uncertainties are estimated as in Fan et al. (2006) by applying the relations in Figure 2 of Carpenter et al. (2001), which shows the observed uncertainty as a function of magnitude for bright stars in the 2MASS JHK bands. In addition, Fan et al. (2006) proved that the adopted uncertainty does not affect the SED fits. \( \sigma_{\text{mod},i} \) represents the uncertainty associated with the model itself, for the \( i \)th filter. Following de Grijs et al. (2005a), Wu et al. (2005), Fan et al. (2006), Ma et al. (2007, 2009), and Wang et al. (2010), we adopt \( \sigma_{\text{mod},i} = 0.05 \).

For clusters without reddening values from the literature, we constrained the ages while keeping \( Z \) and reddening as free parameters, using

\[
\chi^2_{\text{min}}[t, Z, E(B - V)] = \min \left[ \sum_{i=1}^{8} \left( \frac{m_{\text{obs}}^{i} - m_{\text{mod}}^{i}}{\sigma_i} \right)^2 \right]. \tag{4}
\]
We varied the reddening between $E(B-V) = 0.0$ and 2.0 mag in steps of 0.02 mag.

To check the consistency of our reddening estimates with respect to those of Fan et al. (2008) and Barmby et al. (2000), we refitted our cluster SEDs adopting reddening as a free parameter in Equation (4). Figure 7 shows the comparison. We note that the scatter is large, although there is a tendency that our fits with reddening as a free parameter resulted in higher extinction estimates than the values from the literature. In turn, this affects the resulting age estimates through the age–extinction degeneracy: see the right-hand panel of Figure 7, which shows a slight tendency toward younger ages resulting from our “free-reddening” fits than when using the smaller extinction values from the literature (the effect is small because the differences in our extinction estimates are not very large either). It is notoriously difficult to obtain reliable reddening estimates from broadband fits, independent of the wavelength range covered (Anders et al. 2004a; de Grijs et al. 2005a; de Grijs & Anders 2006). de Grijs et al. (2005a) and de Grijs & Anders (2006) compared the systematic differences resulting from using different approaches based on broadband photometry and concluded that the differences are very small. The right-hand panel of Figure 7 provides some support for their earlier conclusion.

To get a rough estimate of the completeness of our photometry, we plot the distribution of absolute (extinction-corrected) $V$ magnitudes of our 445 sample objects in Figure 8. Using a bin size of 0.2 mag, our proxy for the overall limiting magnitude is $M_V = -7$ mag (i.e., the half-peak point of the distribution). In fact, Massey et al. (2006) claimed that the survey reaches $UBVRI \sim 23$ mag, corresponding to $M_V = -1.47$ mag if we adopt a distance modulus of $(m-M)_0 = 24.47$ mag (McConnachie et al. 2005), with <10% uncertainty.

If the initially estimated age of a star cluster is older than 14 Gyr, we adopt an age of 12 Gyr and iterate until the fitting routine reaches a local minimum. It is well known that SSP SEDs are not sensitive to changes in age for ages > 10 Gyr (e.g., Ma et al. 2007). Therefore, although the upper age limit in the BC03 models is 20 Gyr, the ages of the clusters determined here do not exceed 14 Gyr. The estimated ages of the M31 globular-like clusters in our sample are listed in Table 5. We also provide the 1σ errors. When fitting a given parameter, we first fix all other parameters to their best values and fit the minimum $\chi^2$. We subsequently vary the parameter of interest and record an error corresponding to the 1σ $\chi^2$ value.

Figure 9 shows comparisons of our newly derived ages with previous results. The top left-hand panel is a comparison between Puzia et al. (2005) and our results. We note that Puzia et al.’s (2005) cluster ages are systematically older than ours. This may have been caused by their assumption of 13 Gyr as the initial guess for their age iterations, possibly leading to convergence in a different local minimum. (We did not constrain the initial guesses.) The top right-hand panel compares the results of Fan et al. (2006) with our new determinations. We note that the scatter is large, but so are the realistic error bars. Any systematic differences, particularly for younger objects, may be due to the age–metallicity degeneracy affecting broadband SED fitting: we previously adopted metallicities deemed suitable for the old M31 GCs. We show in Figure 11 that this is indeed the case: the metallicity determinations of Perrett et al. (2002), who used Galactic GCs to calibrate their metallicity scale, are systematically more metal-poor than those derived from our SED fits. This could lead to the systematically older ages of Fan et al. (2006). The bottom left-hand panel is a comparison between our new results and those from Caldwell et al. (2009), who only estimated the ages of their young clusters. The agreement is good. The bottom right-hand panel compares our new age estimates with those of Wang et al. (2010), who applied the GALEV SSP models to their SED fits. Both sets of results are consistent, especially for clusters younger than 2 Gyr and within the fairly large uncertainties (cf. de Grijs et al. 2005b).
The spectroscopic age estimates are important for comparison with our work. Caldwell et al. (2009) estimated the ages of 134 young and 367 old clusters. In our sample, the fraction of clusters that are classified by Caldwell et al. (2009) as old/young is 314/29, while the fraction for the same clusters based on our new age determinations is 181/162. Caldwell et al. (2009) did not provide the uncertainties associated with their age estimates. However, if we consider the lower (upper) limits to the ages derived here, the fraction is 169/174 (194/149). In our full sample, this fraction is 224/221. Again, if we consider the uncertainties in our age estimates, we arrive at respective fractions of 210/235 and 244/201. Even if we were to use our reddening-free fitting results, the fraction does not change by much, which means that the reddening values from the literature that we applied in our work do not affect our results significantly. The difference is essentially due to the different methods applied. The similar study of Wang et al. (2010) also shows that the fraction of old/young clusters is low. In addition, the proportion of young clusters in the disk should not be very small, while we also note that a large fraction of our sample should be composed of young massive clusters, rather than typical GCs.

To check our results, we need to compare the metallicities derived from our SED fits with literature values based on spectroscopy. We applied the metallicity estimates from Table 1 of Fan et al. (2008), which contains a summary of the spectro-

Table 5

| Object | Age (Gyr) | $\log(M_\odot)$ | [Fe/H] | $E(B-V)$ (mag) |
|--------|----------|-----------------|--------|----------------|
| AU010  | 8.000 ± 1.000 | 5.195 ± 0.059 | 0.077 ± 0.057 | 0.040 ± 0.010 $^a$ |
| B001   | 5.750 ± 0.875 | 5.421 ± 0.062 | −0.178 ± 0.085 | 0.250 ± 0.020 |
| B002   | 0.045 ± 0.017 | 4.203 ± 0.084 | 0.531 ± 0.099 | 0.500 ± 0.040 $^a$ |
| B003   | 6.250 ± 2.000 | nan ± nan | −7.299 ± 0.156 | 0.190 ± 0.020 |
| B004   | 12.500 ± 5.500 | 5.469 ± 0.159 | −0.490 ± 0.085 | 0.070 ± 0.020 |
| B005   | 2.300 ± 0.300 | 5.688 ± 0.052 | −0.632 ± 0.099 | 0.280 ± 0.020 |
| B006   | 9.500 ± 2.625 | 5.995 ± 0.114 | −0.405 ± 0.085 | 0.090 ± 0.020 |
| B008   | 0.905 ± 0.148 | 5.387 ± 0.039 | −2.022 ± 0.156 | 0.640 ± 0.040 $^a$ |
| B009   | 1.278 ± 0.148 | 4.637 ± 0.067 | −1.171 ± 0.113 | 0.150 ± 0.020 |
| B010   | 12.750 ± 5.250 | 5.615 ± 0.147 | −1.965 ± 0.000 | 0.220 ± 0.010 |

Note. $^a$ Reddening obtained from free fits and not available from Fan et al. (2008) or Barmby et al. (2000).

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)
The cluster age distribution is interesting because it offers a clue to the galaxy’s formation history. Figure 12 shows the age distribution of our sample of globular-like clusters in M31 (bin size: 0.5 Gyr), which is very similar to that of Wang et al. (2010) who obtained the ages of M31 GCs based on a similar SED-fitting method. In the entire sample, 121 and 221 of the 445 star clusters are younger than 1 and 2 Gyr, respectively, corresponding to ≈27 and 50% of the sample (see also Williams & Hodge 2001a, 2001b; Burstein et al. 2004; Beasley et al. 2004; Puzia et al. 2005; Fan et al. 2006; Ma et al. 2009; Caldwell et al. 2009; Wang et al. 2010; Perina et al. 2010). The age distribution of our clusters, combined with those of the younger clusters from previous studies, shows evidence of active star formation in M31 over the past 2 Gyr. This implies that there may have been several star-forming episodes in this period, possibly triggered by major or several minor mergers with other galaxies (see below). In addition, we also find some intermediate-age star clusters, with ages between 3 and 8 Gyr. These intermediate-age counterparts have also been found by Puzia et al. (2005), Fan et al. (2006), Ma et al. (2009), and Wang et al. (2010), but there are some differences between our work and these previous studies. For instance, the intermediate-age (~3–8 Gyr old) cluster population in Puzia et al. (2005) is found to be ~2–5 Gyr in this paper, while our newly determined intermediate-age clusters range from 2 to 20 Gyr in Fan et al. (2006) and from 1 to 10 Gyr in Wang et al. (2010). This is most likely due to the different models and fitting methods applied (cf. de Grijs et al. 2005a). The age distribution of the M31 globular-like clusters is quite different from that of the Milky Way GCs, which are all older than 10 Gyr. In fact, this might be due to our sample selection. Our results are based on observations in the M31 disk, where most of the young clusters are located. We also note that our final sample includes 445 objects that are located in the disk. These disk clusters are usually young and this will cause the distribution to be dominated by the young population. Hammer et al. (2007) pointed out that the Milky Way has had an exceptionally quiet formation history over the last 10 Gyr, which might explain the lack of a significant population of young globular-like clusters in our Galaxy. It may also explain why M31 and the Milky Way have similar sizes, masses, and
Hubble types, but M31 has many more GCs (460 ± 70; Barnby & Huchra 2001) than the Milky Way (>152; Froebrich et al. 2007), i.e., this is probably because M31 underwent a much more extended star formation history than the Milky Way. Ibata et al. (2005) and Hammer et al. (2007) suggested that a recent, active merger may have occurred in M31, which could have triggered GC formation in the interval from ~8 to less than 1 Gyr ago. McConnachie et al. (2009) suggested that an encounter between M33 and M31 took place a few Gyr ago. The clusters with ages in excess of 10 Gyr in Figure 12 were most likely created when the galaxy formed, while the young globular-like clusters might have been created in a number of mergers during the last few Gyr or by the recent galactic encounter with M33.

The peak around 12.5 Gyr in Figure 12 is artificially created by our method of resetting the fits for ages exceeding 14 Gyr. To show this, we plot the age distribution resulting from allowing the model to reach up to 20 Gyr in Figure 13.

We converted the clusters’ angular positions to a linear scale at the distance of M31, 785 kpc (McConnachie et al. 2005). As center coordinates we adopted \( \alpha_{2000} = 00:42:44.3 \) (hh:mm:ss.ss), \( \delta_{2000} = +41:16:09 \) (°:′:″) and we used a position angle of \( \theta = 38° \) (Kent 1989). We find that clusters at projected distances beyond 30 kpc from the galactic center, which corresponds to the disk boundary defined by Racine (1991), are composed of two components, i.e., ~1 and >10 Gyr old populations. These clusters are real halo clusters even when taking into account projection effects. Mackey et al. (2010) studied the M31 halo GCs and concluded that the majority of the halo clusters beyond a projected radius of 30 kpc were accreted from satellite galaxies. However, it is more likely that the older, >10 Gyr old clusters were created when the galaxy formed, while the younger ~1 Gyr old clusters might either have been captured from satellite galaxies or created by mergers and interactions in the last few Gyr. (In principle, a homogeneous data set of cluster metallicities could help distinguish between these scenarios. Unfortunately, the quality of metallicity determinations, either from the literature or based on our SED fits, for our sample clusters is insufficient for this purpose.) On the other hand, for the clusters with projected radii <30 kpc (the disk boundary), we cannot easily distinguish whether they are disk clusters or halo objects projected onto the disk. The ages of the star clusters projected onto the disk range from \( \sim 10^6 \) to \( >10^{10} \) yr.

Figure 14 shows the galactocentric spatial distribution of the young, <2 Gyr old (left-hand panel) and old, >2 Gyr old star clusters (right-hand panel). In the left-hand panel, the squares represent the clusters younger than 1 Gyr, while in the right-hand panel, the circles are clusters older than 10 Gyr. The \( X \) coordinate is defined as the position along the major axis, while the \( Y \) coordinate represents the distance perpendicular to the major axis (see, e.g., Perrett et al. 2002; Wang et al. 2010). Formally,

\[
X = A \sin \theta + B \cos \theta,
\]

\[
Y = -A \cos \theta + B \sin \theta,
\]

\[
A = \sin(\alpha - \alpha_0) \cos \delta,
\]

and

\[
B = \sin \delta \cos \delta_0 - \cos(\alpha - \alpha_0) \cos \delta \sin \delta_0.
\]

To show the spatial distribution of the young clusters and its correlation with the ring structures more clearly, we include Figure 15. The green, solid ellipse and the red, dashed contour represent, respectively, the “10 kpc ring” and the “outer ring” of Gordon et al. (2006) based on infrared observations with the Spitzer Space Telescope’s Multiband Imaging Photometer for Spitzer (MIPS) instrument. In the 10 kpc and outer-ring regions, star formation is very active, and hundreds of YMCs have been created over the last few Gyr. The blue dotted ellipse in Figure 15 represents the disk boundary of M31 (Racine 1991). We find that the YMCs in our sample are spatially coincident with the disk and the spiral arms (for which we use the 10 kpc and outer rings as proxy, respectively), and that the majority of the young clusters (154 out of 221 clusters, 70%) are located in the disk defined by Racine (1991). In Figure 14, note that (in the right-hand panel) the old clusters are located in the galaxy’s bulge and halo, which were both presumably created at the epoch when M31 formed. We also plot the histograms in the \( y \) direction to show the different distributions of the two subsamples. In the left-hand panel, we find the highest-density region in the galaxy center, corresponding to the bulge. There are two lower-density peaks nearby, which may correlate with the 10 kpc “ring of fire” in Figure 15. In the right-hand panel, the distribution is completely different: the density is not as high as
Figure 14. Galactocentric spatial distribution of (left-hand panel) the young (age < 2 Gyr) and (right-hand panel) old (age > 2 Gyr) globular-like star clusters in M31.

Figure 15. Galactocentric spatial distribution of the young (age < 2 Gyr) globular-like star clusters in M31. There are 221 young clusters younger than 2 Gyr in our sample. The green ellipse (solid line) represents the 10 kpc ring, while the red ellipse (dashed line) represents the outer ring (Gordon et al. 2006). The blue ellipse (dotted line) shows the disk boundary defined by Racine (1991).

that of the young population and there are no peaks nearby. This statistical test implies that the spatial distributions of the two populations are different and that the distribution of the young clusters correlates with the galaxy’s ring structure.

Lamers et al. (2005b) show the characteristic cluster disruption time versus ambient density in the disks of M33, the Small Magellanic Cloud, the Milky Way, and M51. We also added the M82 data point from de Grijs et al. (2005b) in Figure 16. The solid line is the theoretical prediction from Baumgardt & Makino (2003) and Portegies Zwart et al. (2001), respectively. For M33, the Small Magellanic Cloud (SMC), the Milky Way (MW), and M51, the data are from Lamers et al. (2005b). For M82, the data are from de Grijs et al. (2005b).

Figure 16. Characteristic cluster disruption time (for \(10^4 M_\odot\) clusters) vs. ambient disk density for five local galaxies. The solid and dashed lines are the theoretical predictions from Baumgardt & Makino (2003) and Portegies Zwart et al. (2001), respectively. For M33, the Small Magellanic Cloud (SMC), the Milky Way (MW), and M51, the data are from Lamers et al. (2005b). For M82, the data are from de Grijs et al. (2005b).

pc\(^{-3}\). However, if we use \(r_{\text{proj}} = 10\) kpc as disk size, the mean disk density is 0.221 \(M_\odot\) pc\(^{-3}\), thus giving us a reasonable uncertainty range. The characteristic cluster disruption time can be derived from Equation (8) of Lamers et al. (2005b). We obtained this disruption timescale, for a cluster of mass \(10^4 M_\odot\), \(\log(t_4/\text{yr}) = 9.47 \pm 0.24 (2.95^{+2.18}_{-1.25} \text{ Gyr})\).

Given the large population of YMCs in M31, it is interesting to assess how long they will likely survive and whether they may eventually become old GCs. Lamers et al. (2005a, 2005b) and Lamers & Gieles (2006) suggest that low-mass star clusters, in particular, will be disrupted by stellar evolution, tidal stripping, spiral-arm shocking, and encounters with giant molecular clouds, especially in galactic disks. Figure 17 shows the dereddened, integrated V-band magnitude versus age diagram for our sample clusters, with theoretical predictions for SSP evolution for given initial masses overlaid. The (red) open squares represent the disk YMCs identified in Figure 15 and the continuous lines are fixed-stellar-mass BC03 models for SSPs of solar metallicity, a Chabrier (2003) IMF, and Padova
Figure 17. Dereddened, integrated V magnitudes and initial cluster (SSP) masses as a function of age for our M31 sample clusters. The red squares represent the disk YMCs (<2 Gyr) identified in Figure 10, while the black circles are the other clusters, i.e., both the old clusters (>2 Gyr) and the young halo clusters. The continuous lines are fixed-stellar-mass models from Bruzual & Charlot (2003) for SSPs of solar metallicity, a Chabrier (2003) IMF, and Padova 1994 evolutionary tracks. The black circles are young halo clusters and clusters older than 2 Gyr.

Using the disruption-time equation of Lamers et al. (2005b), we calculated the relevant disruption times for the young disk clusters in our sample. For clusters with a total mass \( M_{\text{cl}} = 10^3 M_\odot \), the disruption time \( t_{\text{dis}} = 0.71^{+0.52}_{-0.30} \) Gyr, and for \( M_{\text{cl}} = 10^4 \) and \( 10^5 M_\odot \), the corresponding times are \( t_{\text{dis}} = 2.95^{+2.18}_{-1.25} \) and \( 12.3^{+9.1}_{-5.2} \) Gyr, respectively. Very crudely, this suggests that if the initial cluster mass \( M_{\text{cl}} > 10^3 M_\odot \), even star clusters located in the dense M31 disk can survive and evolve into GCs over a Hubble time. We note that most disk YMCs in our sample (red squares) will disrupt in \(<2.24\) Gyr, while all are expected to have been disrupted by \( t < 8.9 \) Gyr. This suggests that none of the M31 disk YMCs will evolve into \( >10 \) Gyr old GCs. The predicted fate of the M31 YMCs agrees reasonably well with the conclusions of Caldwell et al. (2009), although they claimed that most of the young clusters would be disrupted in approximately 1 Gyr, except for some compact and massive objects. These authors assumed that the density of M31’s “ring of fire” is similar to that of the solar neighborhood, where the disruption time is on the order of 1.3 Gyr (Lamers et al. 2005b). Thus, they estimated that most of the M31 YMCs can only survive for approximately 1 Gyr. However, it is more likely that the average density of the entire disk is much lower than that of the “ring of fire,” so that the corresponding disruption time should be much longer.

Figure 18. Mass distributions of globular-like clusters in M31 (top left-hand panel), and GCs in the Milky Way (top right-hand panel), NGC 5128 (bottom left-hand panel), and M33 (bottom right-hand panel).

3.2. Masses of the Globular-like Clusters

The mass-to-light ratio \( (M/L)_V \) values obtained from the spectroscopic age estimates can be combined with our V-band photometry to derive masses for all observed M31 GCs. Reddening values are, of course, also needed for extinction corrections.

We calculated the \( (M/L)_V \) values using the BC03 models, luminosities based on conversion of the V-band fluxes, and a distance modulus of \((m-M)_0 = 24.47\) mag (McConnachie et al. 2005). The resulting masses are listed in Table 5 as well as the metallicity and reddening values applied in our fits. Figure 18 shows the mass distribution for the confirmed M31 clusters in our sample. The peak occurs at \( \log(M_{\text{cl}}/M_\odot) = 5.03 \pm 0.02 \) which is consistent with the peaks in the mass distributions of the old GCs in M31. As can be seen in Figure 18, the lower-mass clusters (\( M_{\text{cl}} < 10^4 M_\odot \)) might be either YMCs or OCs, which suggests that a handful of clusters considered “GCs” in the RBC are, in fact, not old massive M31 GCs. Figure 18 also shows the mass distributions of the NGC 5128 clusters from McLaughlin et al. (2008), the Milky Way GCs based on King-model fits (McLaughlin & van der Marel 2005), and the M33 star clusters from Sarajedini & Mancone (2007). The peak for the M31 cluster masses at \( \log(M_{\text{cl}}/M_\odot) = 5.03 \pm 0.02 \) corresponds to \( M_{\text{cl}} \sim (1.07 \pm 0.05) \times 10^5 M_\odot \). For the Milky Way and NGC 5128 GCs, the peaks occur at \( \log(M_{\text{cl}}/M_\odot) = 5.20 \pm 0.03 \) and 5.55 \pm 0.03, respectively, while for the M33 clusters the distribution seems to be trimodal, with peaks at \( \log(M_{\text{cl}}/M_\odot) = 2.98, 4.15, \) and 5.70, which is likely due to a mixture of OCs, YMCs, and GCs in this sample.

In Figure 19, we compare our newly derived masses for the confirmed, globular-like sample clusters with previous determinations where available (all for young clusters). The left-hand panel is a comparison between Caldwell et al. (2009) and this paper, while the right-hand panel shows a comparison between Perina et al. (2010) and our mass determinations. Note that the cluster masses agree reasonably well among these.
three studies, although our mass estimates are systematically smaller than those of both Caldwell et al. (2009) and Perina et al. (2010). This systematic effect is most likely due to the use of different methods (cf. de Grijs et al. 2005a). In this paper, we compared the continuum shapes (SEDs) with BC03 models to derive the ages, and subsequently used the $M/L_s$ to obtain the cluster masses. In contrast, Caldwell et al. (2009) only used the spectral-line features and the Starburst99 SSP models (Leitherer et al. 1999) to constrain the cluster ages. Perina et al. (2010) estimated cluster masses based on integrated 2MASS $JHK$ photometry, combined with SSP models. The latter authors found that different NIR magnitudes, different IMFs, or different SSP models could all lead to different mass determinations, with an overall accuracy of less than a factor of 3. Obviously, our results agree with Perina et al. (2010) within this uncertainty.

Following de Grijs & Anders (2006) and Wang et al. (2010), we investigated the relationship between the ages and masses of the 445 confirmed globular-like clusters and candidates in our sample (see Figure 20). The solid line is the “fading line” (roughly equivalent to the $\sim 50\%$ completeness limit) based on the BC03 SSP models for solar metallicity for an absolute magnitude of $M_V = -7$ mag, derived from the half–peak point of Figure 8. We note that most of the young clusters lie above the line. A number of old clusters with ages between 1 and 10 Gyr are found below the fading line, which is most likely due to their preferred loci in the galaxy’s halo, where fainter objects are more easily distinguishable than when they are projected onto the bright disk. M078 (identified by a filled circle) is the most extreme outlier. It is very faint ($V_0 = 19.40$ mag) and might, in fact, be a young OC. We also find a number of YMCs (as also noted by Caldwell et al. 2009), which might survive to become old GCs by virtue of their high masses. Note that there are two overdensity regions in this figure, at (1) log(age/yr) $\approx 9.1$ ($\approx 1.28$ Gyr), temporally coincident with the onset of thermally pulsing asymptotic giant branch stars around an age of $\sim 1$ Gyr and (2) at $\approx 13$ Gyr, which represents a cluster population that seems to have formed during the time of the galaxy’s formation.

4. SUMMARY

We have presented an updated $UBVRI$ aperture-photometry catalog for 970 objects in the field of M31, including 965, 967, 965, 953, and 827 in the individual $UBVRI$ bands, respectively, of which 205, 123, 14, 126, and 109 do not have previously published photometry. These objects, including globular-like clusters (GCs and YMCs), cluster candidates, and other types of objects such as stars and galaxies, were selected from the most comprehensive catalog of GCs and candidates, the RBC v.4.0. We obtained our aperture photometry based on archival images from the LGGS (Massey et al. 2006). We find good agreement between our photometry and previous measurements, where available.

By combining our new $UBVRI$ photometry with the optical broadband $UBVRI$ and NIR $JHK$ magnitudes from the RBC v.4.0, we determined the ages for 445 confirmed globular-like and candidate clusters in M31 using a $\chi^2$ minimization technique and employing BC03 theoretical SSP synthesis models. Comparisons involving our sample clusters show that our newly derived ages are consistent with previous determinations. Over one-half of these clusters are young, with ages $< 2$ Gyr, implying recent, active star formation in M31. This is consistent with recent results invoking encounters and/or mergers with other galaxies. This is quite different from the age distribution of the Milky Way’s GC system, implying different evolutionary histories for M31 and the Milky Way.

The clusters in the halo ($r_{proj} > 30$ kpc) are composed of two populations, old GCs with ages $> 10$ Gyr and young, $\sim 1$ Gyr old clusters, suggesting that the globular-like clusters in M31 are formed at two different epochs. The spatial distribution of our sample clusters suggests that YMCs with ages $< 2$ Gyr are spatially coincident with the disk (and a few with the halo) of M31, while the old star clusters ($> 2$ Gyr) are spatially correlated with the bulge and halo. We find that none of the young disk clusters can survive to become old GCs after a Hubble time; instead, they will likely encounter giant molecular clouds in the galaxy’s disk and disperse as field stars on timescales of a few Gyr.

We also estimated the masses of the 445 confirmed globular-like clusters and candidates in our sample using the derived ages and BC03 theoretical $M/L_s$, combined with our new photometry from the LGGS. The comparisons show that our estimates agree well with previous results, where available. We calculated the characteristic disruption timescales for the young disk clusters (age $< 2$ Gyr) in M31 and found that disk YMCs with a mass of $10^4 M_\odot$ are expected to dissolve within 3.0 Gyr and will, thus, not evolve into old GCs.

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