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NEW *UBVRI* PHOTOMETRY OF 234 M33 STAR CLUSTERS

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ABSTRACT

This is the second paper of our series. In this paper, we present *UBVRI* photometry for 234 star clusters in the field of M33. For most of these star clusters, there is photometry in only two bands in previous studies. The photometry of these star clusters is performed using archival images from the Local Group Galaxies Survey, which covers 0.8 $\deg^2$ along the major axis of M33. Detailed comparisons show that, in general, our photometry is consistent with previous measurements, and in particular that our photometry is in good agreement with that of Zloczewski & Kaluzny. Combined with star cluster photometry in previous studies, we present some results: none of the M33 youngest clusters ($\sim 10^7$ yr) have masses approaching $10^5\ M_\odot$, and comparisons with models of simple stellar populations suggest a large range of ages for M33 star clusters and some as old as the Galactic globular clusters.

Key words: catalogs – galaxies: individual (M33) – galaxies: spiral

Online-only material: machine-readable and VO tables

1. INTRODUCTION

Star clusters are an important tool for studying the star formation histories of galaxies. They represent, in distinct and luminous "packets," single-age and single-abundance points and encapsulate at least a partial history of the parent galaxy's evolution.

M33 is a small Scd Local Group galaxy. It is located $\sim 809 \pm 24$ kpc from us (distance modulus $(m - M)_0 = 24.54 \pm 0.06$; McConnachie et al. 2004, 2005). M33 is interesting and important because it represents an intermediate morphological type between the largest "early-type" spirals and the dwarf irregulars in the Local Group. Therefore, it can provide an important link between the star cluster populations of earlier-type spirals (Milky Way and M31) and the numerous nearby later-type dwarf galaxies.

In the pioneering work of M33 star clusters, Hiltner (1960) presented photometry for 23 M33 star cluster candidates and 23 M31 globular clusters in the *UBV* passbands using photographic plates taken with the Mt. Wilson 100 inch (2.5 m) telescope. He found that, except for five of them, the star clusters in M33 are bluer and fainter than those in M31. At the same time, Kron & Mayall (1960) identified four M33 star clusters for which they provided *PV* photometry. Then, Melnick & D'Odorico (1978) detected 58 star cluster candidates in M33 based on a baked IIIa-J+GG385 plate covering a field about 1° in diameter, including their *B* photometry. The most comprehensive catalog of nonstellar objects in M33 was compiled by Christian & Schommer (1982, 1988), who detected 250 nonstellar objects by visually examining a single photographic plate taken at the Ritchey-Chrestien focus of the 4 m telescope at Kitt Peak National Observatory. These authors obtained ground-based *BVI* photometry of 106 of these objects, which they believe to be star clusters. However, the star cluster candidates detected by these authors were limited to the outer part of M33.

The first survey for M33 star clusters based on CCD imaging was performed by Mochejska et al. (1998), using the data collected in the DIRECT project (Kaluzny et al. 1998; Stanek et al. 1998). These authors detected 51 globular cluster candidates in M33, 32 of which were not previously cataloged. These globular cluster candidates covered the central region of M33. In addition, Mochejska et al. (1998) presented *BVI* photometry for these globular cluster candidates.

Since the pioneering work of Chandar et al. (1999a), the era of detecting and studying M33 star clusters based on images taken with the *Hubble Space Telescope* (*HST*) has begun (Chandar et al. 1999a, 1999b, 1999c, 2001, 2002; Bedin et al. 2005; Park & Lee 2007; Sarajedini et al. 2007, 1998, 2000; Stonkutė et al. 2008; Park et al. 2009; Huxor et al. 2009; San Roman et al. 2009; Zloczewski & Kaluzny 2009). The *HST* resolution makes it easy to distinguish individual stars from star clusters at the distance of M33. Therefore, M33 star clusters identified with *HST* images are much less likely to be contaminated by other extended sources, such as a background galaxy or an H II region (see Park & Lee 2007 for details).

Ma et al. (2001, 2002a, 2002b, 2002c, 2002d, 2004a, 2004b) constructed spectral energy distributions in 13 intermediate filters of the Beijing–Arizona–Taiwan–Connecticut photometric system for known M33 star clusters and star cluster candidates, and estimated the star clusters' properties.

In order to construct a single master catalog incorporating the entries in all of the individual catalogs including all known properties of each star cluster, Sarajedini & Mancone (2007) merged all of the abovementioned catalogs before 2007, for a summary of the properties of all of these catalogs. This catalog contains 451 star cluster candidates, of which 255 are confirmed star clusters based on *HST* and high-resolution ground-based imaging. The positions of the star clusters in Sarajedini & Mancone (2007) were transformed to the J2000.0 epoch and refined using the Local Group Galaxies Survey (LGGS; Massey et al. 2006).

Very recently, some authors used the images observed with the MegaCam camera on the 3.6 m Canada–France–Hawaii Telescope (CFHT/MegaCam) to detect star clusters in M33 (Zloczewski et al. 2008; San Roman et al. 2010). Sharina et al. (2010) presented the evolutionary parameters of 15 globular clusters in M33 based on the results of medium-resolution spectroscopy obtained at the Special Astrophysical Observatory 6 m telescope. Most recently, Cockcroft et al. (2011) searched for outer halo star clusters in M33 based on CFHT/MegaCam imaging as part of the Pan-Andromeda Archaeological Survey.

Ma (2012, Paper I) presented *UBVRI* photometry of 392 objects (277 star clusters and 115 star cluster candidates) in the field of M33, using the images of the LGGS (Massey et al. 2006). He also provided properties of M33 star clusters such as their color–magnitude diagram (CMD) and color–color diagram.

In this paper, we perform aperture photometry of 234 M33 star clusters based on the M33 images of LGGS. These sample star clusters are selected from Park & Lee (2007), San Roman et al. (2009), and Zloczewski & Kaluzny (2009). This paper is organized as follows. Section 2 describes the sample star cluster selection and *UBVRI* photometry. In Section 3, we present an analysis of the star cluster properties. Last, our conclusions are presented in Section 4.

2. DATA

2.1. Sample

In Paper I, we presented an updated *UBVRI* photometric catalog containing 392 star clusters and star cluster candidates in the field of M33 which were selected from the most recent star cluster catalog of Sarajedini & Mancone (2007). We also provided properties of M33 star clusters such as their CMD and color–color diagram combined with the photometry of M33 star clusters from Park & Lee (2007), San Roman et al. (2009), and Zloczewski & Kaluzny (2009). However, we found that most M33 star clusters from San Roman et al. (2009) and Zloczewski & Kaluzny (2009) have photometry in only two bands, *V* and *I*. In the color–color diagram of Paper I, there are only ∼300 M33 star clusters, since ∼200 star clusters have no $B-V$ data. Therefore, the integrated magnitudes of these star clusters in the *B* and *V* bands are urgently needed for studying the properties of M33 star clusters. In this paper, we will provide *UBVRI* photometry of M33 star clusters from Park & Lee (2007), San Roman et al. (2009), and Zloczewski & Kaluzny (2009). Park & Lee (2007) found 104 star clusters in the *HST*/WFPC 2 archive images of 24 fields that were not included in previous studies, of which 32 star clusters are newly detected. Zloczewski et al. (2008) presented a catalog of 4780 extended sources in a 1 deg^2 region around M33, including 3554 new star cluster candidates using the MegaCam camera on the CFHT. Zloczewski & Kaluzny (2009) used deep Advanced Camera for Surveys Wide Field Channel (ACS/WFC) images of M33 to check the nature of extended objects detected by Zloczewski et al. (2008), and found that 24 star cluster candidates were confirmed to be genuine compact star clusters. In addition, Zloczewski & Kaluzny (2009) detected 91 new star clusters based on these deep ASC/WFC images of M33, and provided integrated magnitudes and angular sizes for all of these 115 star clusters. San Roman et al. (2009) presented integrated photometry and CMDs for 161 star clusters in M33 based on the ACS/WFC images, of which 115 were previously uncataloged. By cross-checking with the updated photometric catalog of M33 star clusters and candidates in Paper I, we found that the photometry of 36 star clusters by Park & Lee (2007) was not presented in Paper I, of which 32 star clusters were newly detected by Park & Lee (2007) and the remaining four were detected by previous studies. Three of the four star clusters were included in Sarajedini & Mancone (2007) and were classified as "Stellar" (objects 69, 293, and 279 of Sarajedini & Mancone 2007, which are called star clusters 36, 195, and 197 in Park & Lee 2007, respectively), and the remaining one is star cluster 75 in Park & Lee (2007). The photometry of 118 star clusters in San Roman et al. (2009) was not presented in Paper I, of which 115 star clusters were newly detected by San Roman et al. (2009) based on the ACS/WFC images, and the remaining three star clusters were included in Sarajedini & Mancone (2007), which were classified as "Galaxy" or "Stellar" (objects 57, 62, and 69 of Sarajedini & Mancone 2007, which are called star clusters 27, 34, and 38 in San Roman et al. 2009). The photometry of all star clusters in Zloczewski & Kaluzny (2009) was not presented in Paper I, of which one star cluster was included in Sarajedini & Mancone (2007) and was classified as "Galaxy" (object 57 of Sarajedini & Mancone 2007, which is called 33-3-021 in Zloczewski & Kaluzny 2009). Therefore, in this paper, we will perform photometry for the M33 star clusters in Park & Lee (2007), Zloczewski & Kaluzny (2009), and San Roman et al. (2009) that were not presented in Paper I. Altogether, there are 269 star clusters, combining the star clusters from Park & Lee (2007), Zloczewski & Kaluzny (2009), and San Roman et al. (2009). However, by cross-checking the coordinates of the star clusters of Park & Lee (2007), Zloczewski & Kaluzny (2009), and San Roman et al. (2009), and by checking the images of star clusters from LGGS, we found that star clusters 7, 10, 14, and 18 in Park & Lee (2007) are the same objects as star clusters 33, 51, 59, and 64 in San Roman et al. (2009), respectively. In addition, there are 18 common star clusters between Zloczewski & Kaluzny (2009) and San Roman et al. (2009; see Table 3 of San Roman et al. 2009). When we perform photometry of the sample star clusters in this paper, we find that there is nothing in the position of star cluster 195 in Park & Lee (2007; i.e., No. 17 of Bedin et al. 2005), which was named object 293 in Sarajedini & Mancone (2007) and which they classified as "Stellar". We also find that, in the LGGS images of M33, (1) there are some bright objects near star cluster 12 in Park & Lee (2007); (2) there is a bright object near star clusters 23 and 32 in Park & Lee (2007), respectively; (3) there is a bright object very near star clusters 15, 114, and 141 in San Roman et al. (2009), respectively; (4) there are three bright objects near star cluster 143 in San Roman et al. (2009); and (5) there is a very close object to star clusters ZK-21, ZK-22, ZK-28, ZK-66, and ZK-72 in Zloczewski & Kaluzny (2009), respectively. The photometry of these 13 star clusters cannot be determined accurately in this paper. Therefore, this paper will present homogeneous *UBVRI* photometry of 234 star clusters in M33 using the images from LGGS (see details about LGGS in Paper I). Figure 1 shows the spatial distribution of 234 star clusters in the LGGS fields. The large ellipse is the D_{25} boundary of the M33 disk (de Vaucouleurs et al. 1991). The three large squares are the LGGS field boundaries.

2.2. Photometry

We used the LGGS archival images of M33 in the *UBVRI* bands to perform the photometry (see details in Paper I). We performed aperture photometry of the 234 M33 star clusters found in the LGGS images in all of the *UBVRI* bands to provide a comprehensive and homogeneous photometric catalog for them. The photometry routine we used is IRAF/DAOPHOT (Stetson 1987). The photometric process used in this paper is the same as in Paper I. We have checked the aperture of every sample star cluster considered here by visual examination to make sure that it was not too large (to avoid contamination from other sources). The aperture photometry of star clusters was transformed to the standard system using transformation (constant offsets neglecting color term) derived from aperture photometry of stars whose *UBVRI* magnitudes were published

Table 1
New *UBVRI* Photometry of 234 M33 Star Clusters

ID	ID	ID	ID	ID	R.A. (J2000.0)	Decl. (J2000.0)	U (mag)	B (mag)	V (mag)	R_C (mag)	I_C (mag)	$E(B-V)$ (mag)	r_{ap} (″)
1......	PL1				01 32 36.337	30 36 49.41	18.751 ± 0.010	19.887 ± 0.029	19.588 ± 0.029	19.076 ± 0.022	19.118 ± 0.029	0.20	2.838
2......	PL2				01 33 11.809	30 38 57.03	16.677 ± 0.017	17.536 ± 0.018	17.326 ± 0.018	17.129 ± 0.018	17.429 ± 0.020	0.10	2.064
3......	PL3				01 33 12.732	30 38 55.69	18.556 ± 0.016	19.075 ± 0.021	18.894 ± 0.024	18.777 ± 0.024	18.472 ± 0.023	0.10	2.064
4......	PL4				01 33 15.038	30 39 04.94	18.604 ± 0.017	18.918 ± 0.019	18.463 ± 0.018	18.092 ± 0.018	17.700 ± 0.017	0.15	3.354
5......	PL5				01 33 19.558	30 35 30.00	17.135 ± 0.006	17.409 ± 0.007	17.118 ± 0.006	16.951 ± 0.006	16.673 ± 0.006	0.10	2.322
6......	PL6				01 33 20.274	30 34 49.96	17.246 ± 0.006	17.756 ± 0.011	17.570 ± 0.011	17.531 ± 0.014	17.308 ± 0.018	0.10	4.128
7......	PL7		SR33		01 33 21.388	30 31 12.84	18.846 ± 0.013	19.219 ± 0.021	18.882 ± 0.019	18.699 ± 0.022	18.371 ± 0.022	0.08	2.322
8......	PL8				01 33 22.398	30 35 29.93	20.540 ± 0.039	20.667 ± 0.054	20.206 ± 0.051	19.612 ± 0.043	19.136 ± 0.045	0.10	2.064
9......	PL9				01 33 23.195	30 52 42.51	19.889 ± 0.024	19.850 ± 0.024	19.335 ± 0.023	18.953 ± 0.022	18.578 ± 0.022	0.15	3.096
10......	PL10		SR51		01 33 26.634	30 31 30.35	18.199 ± 0.014	18.527 ± 0.019	18.148 ± 0.018	17.844 ± 0.018	17.455 ± 0.018	0.09	3.870

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

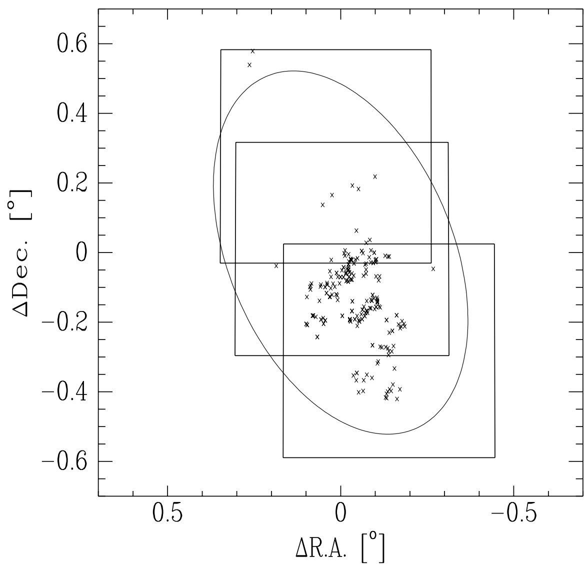

Figure 1. Spatial distribution of the 234 star clusters of M33, which were selected from Park & Lee (2007), San Roman et al. (2009), and Zloczewski & Kaluzny (2009) and their loci in the LGGS fields. We determined the photometry for these star clusters based on the LGGS archival images of M33 in the *UBVRI* bands. The large ellipse is the D_{25} boundary of the M33 disk (de Vaucouleurs et al. 1991). The three large squares are the LGGS fields.

Table 2
Comparison between this Study and Previous studies of *V* Photometry for M33 Star Clusters Considered Here

ID[a]	ID[b]	V^c (mag)	V^d (mag)	V^e (mag)	ΔV^f (mag)	ΔV^g (mag)	$r_{ap}{}^h$ (″)
PL197		17.652 ± 0.003		20.384 ± 0.056	2.732		1.032
SR5	25-1-003	19.768	20.41	20.951 ± 0.087	1.183	0.541	1.290
SR16	33-5-019	20.352	21.16	21.663 ± 0.113	1.311	0.503	2.580
SR45		20.063		21.159 ± 0.060	1.095		1.548
SR50		19.530		20.670 ± 0.174	1.140		2.580
SR58		19.514		20.601 ± 0.047	1.087		1.548
SR116		18.405		19.566 ± 0.046	1.161		1.548
SR118		18.151		19.533 ± 0.066	1.382		1.290

Notes.
[a] Star cluster names following the naming convention of Park & Lee (2007) or San Roman et al. (2009).
[b] Star cluster names following the naming convention of Zloczewski & Kaluzny (2009).
[c] Photometry obtained by Park & Lee (2007) or by San Roman et al. (2009).
[d] Photometry obtained by Zloczewski & Kaluzny (2009).
[e] Photometry obtained in this paper.
[f] Magnitude difference between this study and Park & Lee (2007) or San Roman et al. (2009) (this study minus Park & Lee 2007 or San Roman et al. 2009).
[g] Magnitude difference between this study and Zloczewski & Kaluzny (2009) (this study minus Zloczewski & Kaluzny 2009).
[h] Aperture radius of photometry adopted in this paper.

by Massey et al. (2006), who calibrated their photometry with the standard stars of Landolt (1992). Finally, except for star cluster 27 of San Roman et al. (2009; i.e., SR27, which was named 33-3-021 in Zloczewski & Kaluzny 2009) and ZK-82 of Zloczewski & Kaluzny (2009) in the *I* band, and ZK-90 of Zloczewski & Kaluzny (2009) in the *U* and *I* bands, we obtained photometry for 234 star clusters in the individual *UBVRI* bands. SR27 falls in the gap of the LGGS image in the *I* band, and ZK-82 and ZK-90 in the *I* band fall in the bleeding CCD column of a saturated star, and ZK-90 in the *U* band does not appear in the LGGS image. Table 1 lists our new *UBVRI* magnitudes and the aperture radii used (we adopted 0.″258 pixel^{-1} from the image header), with errors given by IRAF/DAOPHOT. The star cluster names follow the naming convention in Sarajedini & Mancone (2007; i.e., SM × ××), Park & Lee (2007; i.e., PL × ××), San Roman et al. (2009; i.e., SR × ××), and Zloczewski & Kaluzny (2009). In addition, we also list the reddening values of the sample star clusters in Table 1 (see Section 3.1 for details). In Table 1, R_C and I_C mean that the RI magnitudes are in Johnson–Kron–Cousins system.

To examine the quality and reliability of our photometry, we compared the aperture magnitudes of the 234 star clusters obtained here with previous photometry from Park & Lee (2007), San Roman et al. (2009), and Zloczewski & Kaluzny (2009). There are eight star clusters, of which the magnitude scatters in the *V* band between this study and the previous studies of Park & Lee (2007) and San Roman et al. (2009) are larger than 1.0 mag, i.e., our magnitudes are fainter than those obtained by Park & Lee (2007) and San Roman et al. (2009). We listed the comparison between this study and previous studies of *V* photometry for these eight star clusters in Table 2. We also plotted their images in Figure 2, in which the circles are photometric apertures adopted here. From this figure, we can see that nearly all of these star clusters are close to one or more bright sources. If photometric apertures are larger than the values adopted here, the light from these bright sources will not be excluded. We know, from Park & Lee (2007), that the *BVI* integrated aperture photometry of M33 star clusters, which is included in the 50′ × 80′ field of M33 based on CCD images taken with the CFH12k mosaic camera on CFHT, is

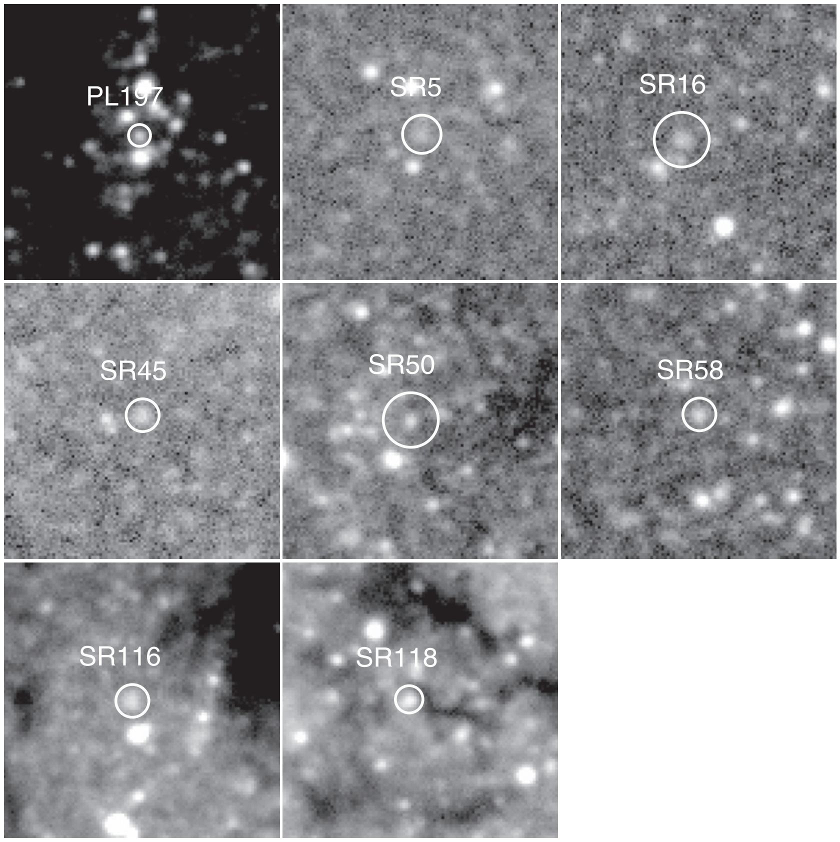

Figure 2. Finding charts of eight star clusters in the LGGS *V* band, of which the magnitude scatters in the *V* band between this study and Park & Lee (2007) and San Roman et al. (2009) are larger than 1.0 mag, i.e., our measurements are fainter than those in Park & Lee (2007) and San Roman et al. (2009). The circles are photometric apertures adopted in this paper.

derived with an aperture of $r = 4\farcs0$ for the V magnitude measurement and an aperture of $r = 2\farcs0$ for the measurement of color. San Roman et al. (2009) derived integrated photometry and CMDs for 161 star clusters in M33 using the ACS/WFC images. These authors adopted an aperture radius of $r = 2\farcs2$ for V magnitude measurements and $r = 1\farcs5$ for the colors. For these eight star clusters, a large scatter in the V photometric measurement between this study and previous studies (Park & Lee 2007; San Roman et al. 2009) mainly results from different photometric aperture sizes adopted by different authors (see Paper I for details). Figures 3–5 show the comparison of our photometry of the star clusters with the previous photometry of Park & Lee (2007), San Roman et al. (2009), and Zloczewski & Kaluzny (2009). PL197 is not included in the ΔV comparison in Figure 3 because the value of ΔV is too large to be drawn in the figure. In addition, in Figure 5 (and Figures 6, 8, and 9 below), we have transformed the ACS/WFC magnitudes in F475W, F606W, and F814W bands to the Johnson–Cousins B, V, and I magnitudes using the color-dependent synthetic transformations given by Sirianni et al. (2005).

From Figures 3–5, we can see that our measurements in the V band get systematically fainter than the photometric measurements in San Roman et al. (2009) for fainter sources ($V \geqslant 19$ mag). The $(V - I)$ colors obtained here are in good agreement with those in Park & Lee (2007) and San Roman et al. (2009); however, the difference between the $(B - V)$ colors in San Roman et al. (2009) and this paper is large, which turned out to be 0.388 ± 0.040 with $\sigma = 0.268$. From Figure 5, we can see that both the $(B - V)$ and $(V - I)$ colors obtained here are in good agreement with those in Zloczewski & Kaluzny (2009); however, the V difference between this study and Zloczewski & Kaluzny (2009) turned out to be -0.103 ± 0.026 with $\sigma = 0.262$. By cross-identification, San Roman et al. (2009) provided 21 common star clusters in Zloczewski & Kaluzny (2009). We derived photometry for 18 of these 21 star clusters. We compared the photometry of these 18 star clusters with previous measurements in San Roman et al. (2009) and Zloczewski & Kaluzny (2009) for comparison. Figure 6 shows the comparison. From Figure 6, we can see that our measurements in the V band get systematically fainter than the photometric measurements in San Roman et al. (2009) for fainter sources ($V \geqslant 19$ mag); however, this trend disappears between this study and Zloczewski & Kaluzny (2009). Both the $(B - V)$ and the $(V - I)$ colors obtained here are in good agreement with those in San Roman et al. (2009) and Zloczewski & Kaluzny (2009). In Paper I, we discussed the V difference between his study and previous studies in detail, and showed that the V difference resulted from different photometric apertures adopted in his study and previous studies. In Paper I, we showed that if the photometric apertures were adopted in our study to be the same as previous studies, the V difference disappeared.

3. RESULTS

In Paper I, we presented some results for M33 star clusters, including the CMD and color–color diagram. In addition, in Paper I we pointed out that, before Zloczewski & Kaluzny (2009), none of the M33 star clusters with $V > 21.0$ mag have been detected. In addition, Zloczewski & Kaluzny (2009) emphasized that the faintest known globular cluster in the

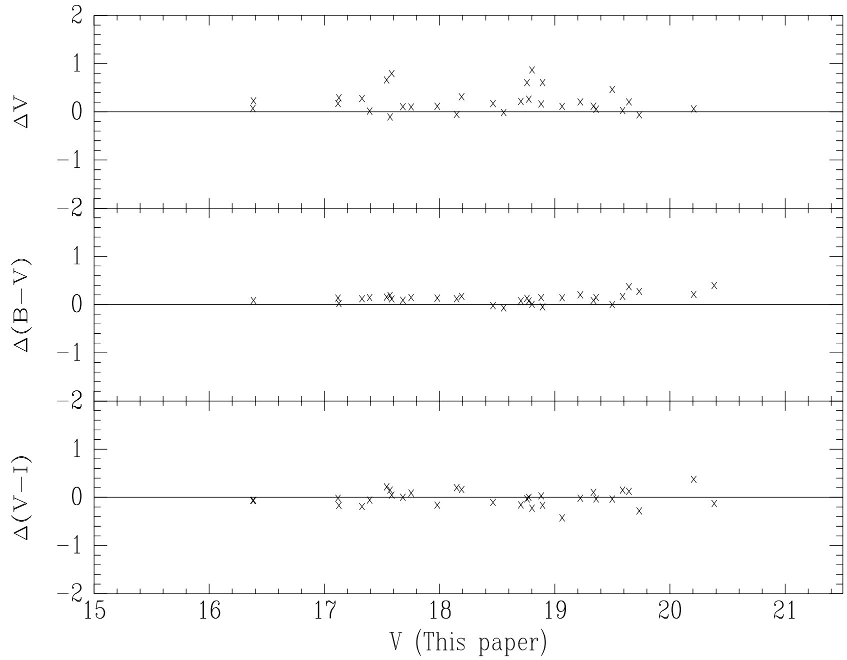

Figure 3. Comparison of our photometry of M33 star clusters in the *UBVRI* bands with previous photometry in Park & Lee (2007). The photometric offsets and rms scatter of the differences between their measurements and our new magnitudes are $\Delta V = 0.306 \pm 0.089$ with $\sigma = 0.498$, $\Delta(B - V) = 0.126 \pm 0.019$ with $\sigma = 0.102$, and $\Delta(V - I) = -0.023 \pm 0.030$ with $\sigma = 0.162$ (this study minus Park & Lee 2007).

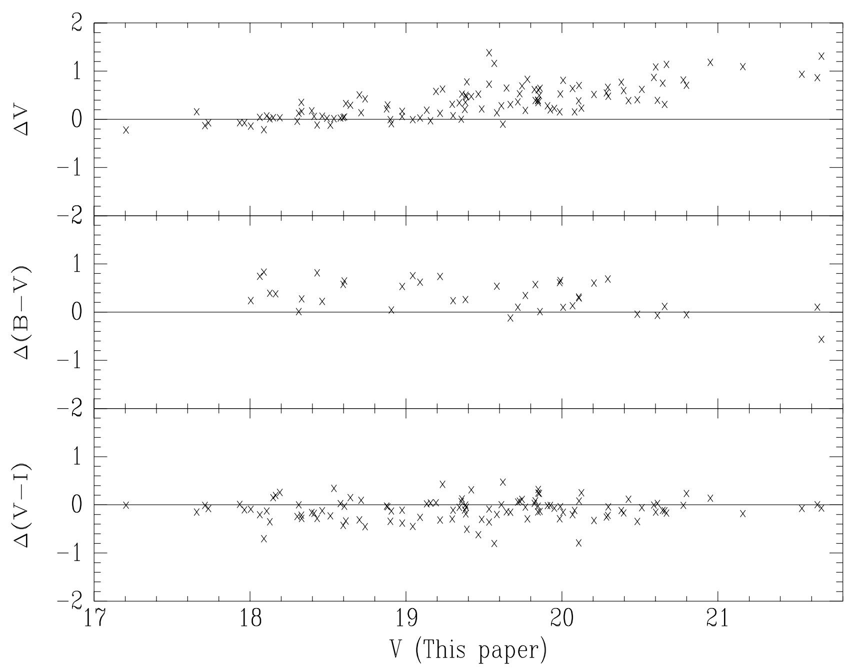

Figure 4. Comparison of our photometry of M33 star clusters in the *UBVRI* bands with previous photometry in San Roman et al. (2009). The photometric offsets and rms scatter of the differences between their measurements and our new magnitudes are $\Delta V = 0.363 \pm 0.033$ with $\sigma = 0.352$, $\Delta(B - V) = 0.332 \pm 0.052$ with $\sigma = 0.316$, and $\Delta(V - I) = -0.100 \pm 0.021$ with $\sigma = 0.244$ (this study minus San Roman et al. 2009).

Milky Way has $M_V \sim -1$ mag comparing with $M_V \sim -4$ mag ($V \sim 21$ mag) observed for the faintest of the known M33 globular cluster candidates before Zloczewski & Kaluzny (2009). Zloczewski & Kaluzny (2009) provided integrated magnitudes for 115 M33 star clusters using ACS/WFC images, of which 9 have 21.0 mag $<$ V $<$ 22.0 mag corresponding to -4 mag $< M_V < -3$ mag. Although the faintest star cluster of M33 detected by Zloczewski & Kaluzny (2009) is 2.0 mag brighter than the faintest Galactic globular cluster, it would be unique for the analysis of M33 star clusters to include them. In fact, Paper I included the photometry of the M33 star clusters in Zloczewski & Kaluzny (2009) when we provided the results for M33 star clusters; however, most star clusters in Zloczewski & Kaluzny (2009) have photometry in only two bands (*V* and *I*). There are only 19 sample star clusters from Zloczewski & Kaluzny (2009) in the color–color diagram provided in Paper I. In addition, most star clusters in San Roman et al. (2009) also have photometry in only two bands (*V* and *I*). Therefore, it is necessary for us to re-provide a CMD and a color–color diagram of M33 including photometry obtained in this paper.

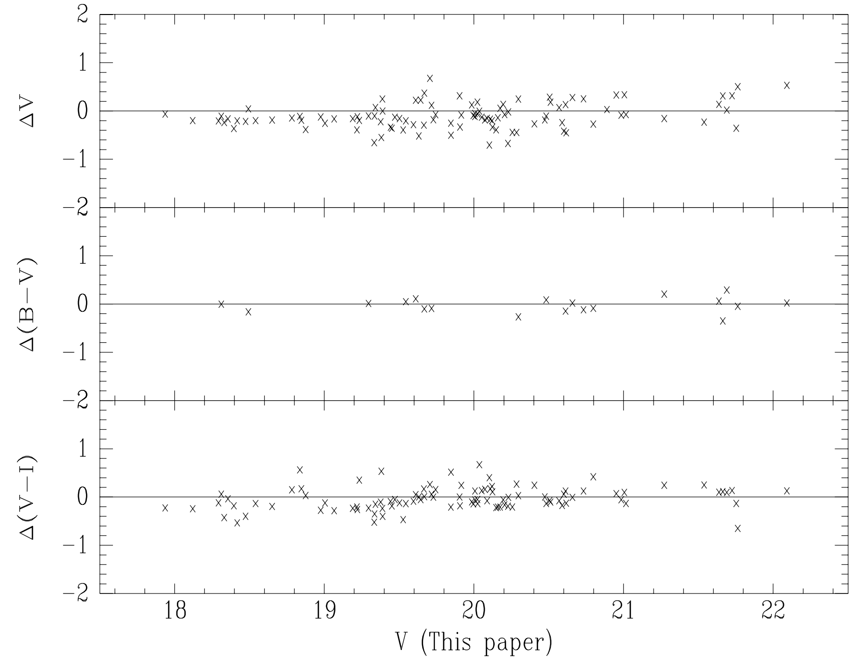

Figure 5. Comparison of our photometry of M33 star clusters in the *UBVRI* bands with previous photometry in Zloczewski & Kaluzny (2009). The photometric offsets and rms scatter of the differences between their measurements and our new magnitudes are $\Delta V = -0.103 \pm 0.026$ with $\sigma = 0.262$, $\Delta(B - V) = -0.028 \pm 0.035$ with $\sigma = 0.149$, and $\Delta(V - I) = -0.032 \pm 0.023$ with $\sigma = 0.234$ (this study minus Zloczewski & Kaluzny 2009).

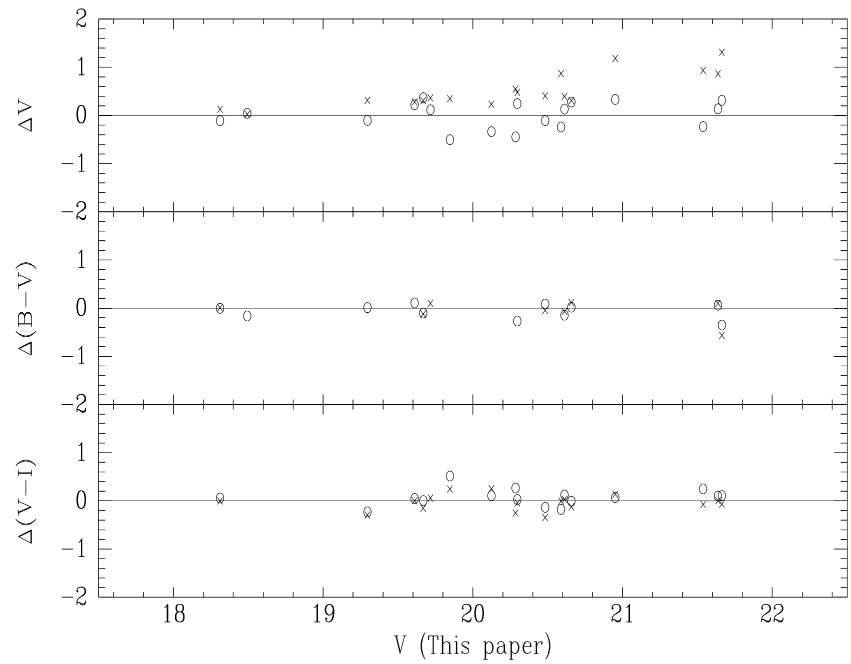

Figure 6. Comparisons of our photometry of M33 star clusters in the *UBVRI* bands with previous measurements in San Roman et al. (2009) and Zloczewski & Kaluzny (2009). Crosses and circles represent the photometry difference between this study and the previous study of San Roman et al. (2009), and the photometry difference between this study and previous study of Zloczewski & Kaluzny (2009), respectively. The photometric offsets and rms scatter of the differences between their measurements and our new magnitudes are $\Delta V = 0.517 \pm 0.086$ with $\sigma = 0.353$, $\Delta(B - V) = -0.050 \pm 0.079$ with $\sigma = 0.208$, and $\Delta(V - I) = -0.037 \pm 0.040$ with $\sigma = 0.161$ (this study minus San Roman et al. 2009); and $\Delta V = 0.006 \pm 0.065$ with $\sigma = 0.268$, $\Delta(B - V) = -0.068 \pm 0.045$ with $\sigma = 0.143$, and $\Delta(V - I) = 0.071 \pm 0.045$ with $\sigma = 0.173$ (this study minus Zloczewski & Kaluzny 2009).

3.1. Color–Magnitude Diagram

The CMD can provide a qualitative model-independent global indication of cluster-formation history that can be compared between galaxies because $(B - V)_0$ and $(V - I)_0$ are reasonably good age indicators, at least between young and old populations, with a secondary dependence on metallicity (Chandar et al. 1999b). CMDs of M33 star clusters have previously been discussed in the literature (Christian & Schommer 1982, 1988; Chandar et al. 1999b; Park & Lee 2007; Paper I). However, with a much larger star cluster sample in this paper, it is worth investigating them again. This paper includes 523 M33 star clusters, of which the photometry of 234 and 277 of them is derived in this paper and in Paper I, respectively, and the photometry of the remaining 12 star clusters is from Park & Lee

Table 3
UBVRI Photometry of 277 M33 Star Clusters in Ma (2012)

ID	ID	ID	ID	R.A. (J2000.0)	Decl. (J2000.0)	U (mag)	B (mag)	V (mag)	R_C (mag)	I_C (mag)	$E(B-V)$ (mag)	r_{ap} ($''$)
235......	SM3	PL33		01 32 34.430	30 37 42.61	21.184 ± 0.053	21.087 ± 0.064	20.419 ± 0.042	20.107 ± 0.041	19.807 ± 0.037	0.05	2.322
236......	SM6	PL105		01 32 38.977	30 39 18.03	20.223 ± 0.035	20.276 ± 0.047	19.767 ± 0.042	19.444 ± 0.038	18.970 ± 0.032	0.10	3.096
237......	SM9			01 32 42.944	30 35 38.67	17.912 ± 0.007	18.016 ± 0.009	17.609 ± 0.008	17.331 ± 0.007	16.929 ± 0.006	0.10	3.612
238......	SM10	PL106		01 32 44.302	30 40 12.33	19.741 ± 0.028	19.597 ± 0.025	18.780 ± 0.017	18.294 ± 0.016	17.676 ± 0.011	0.10	3.096
239......	SM15			01 32 51.818	30 29 36.52	18.937 ± 0.015	18.985 ± 0.020	18.512 ± 0.015	18.178 ± 0.013	17.724 ± 0.012	0.10	3.354
240......	SM16			01 32 52.644	30 14 30.97	19.114 ± 0.010	19.191 ± 0.012	18.842 ± 0.010	18.640 ± 0.011	18.304 ± 0.011	0.10	2.580
241......	SM23			01 32 55.473	30 29 22.34	19.436 ± 0.017	19.765 ± 0.026	19.545 ± 0.025	19.280 ± 0.024	18.666 ± 0.018	0.10	2.064
242......	SM26			01 32 56.323	30 14 58.94	18.171 ± 0.007	18.125 ± 0.007	17.752 ± 0.007	17.536 ± 0.007	17.215 ± 0.009	0.10	4.128
243......	SM28			01 32 57.600	30 55 42.72	20.833 ± 0.035	20.597 ± 0.032	19.840 ± 0.025	19.351 ± 0.021	18.948 ± 0.021	0.10	2.838
244......	SM29			01 32 58.626	30 47 57.23	19.454 ± 0.013	19.528 ± 0.015	19.273 ± 0.016	19.222 ± 0.019	19.032 ± 0.021	0.10	2.580

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

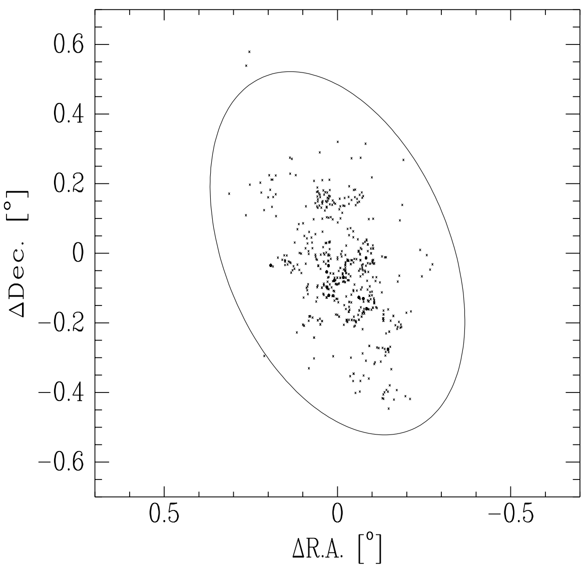

Figure 7. Spatial distribution of the 523 star clusters in M33. Crosses denote the star clusters, the photometry of which is obtained in Paper I and this study, and filled circles denote the star clusters, the photometry of which was obtained by Park & Lee (2007), San Roman et al. (2009), and Zloczewski & Kaluzny (2009). The large ellipse is the D_{25} boundary of the M33 disk (de Vaucouleurs et al. 1991).

(2007), San Roman et al. (2009), and Zloczewski & Kaluzny (2009), since we cannot accurately derive the photometry for these 12 star clusters (see Section 2.2 for details). The 277 star clusters from Paper I are confirmed by Sarajedini & Mancone (2007; 254 star clusters), Park & Lee (2007; 7 star clusters), and San Roman et al. (2009; 16 star clusters) based on *HST* and high-resolution ground-based imaging.

We point out that the photometry of M33 star clusters obtained in Paper I and in this study is homogeneous photometric data in the same photometric system. For completeness of data and reader reference, we list the photometry of 277 star clusters in Paper I in Table 3, including the reddening values from Park & Lee (2007) and San Roman et al. (2009) in Column 9 (Table 3 includes the $E(B-V)$ missed in Paper I). In Table 3, R_C and I_C mean that the RI magnitudes are in the Johnson–Kron–Cousins system. For the reddening values of the star clusters, we used those from Park & Lee (2007) or San Roman et al. (2009). For the star clusters, Park & Lee (2007) and San Roman et al. (2009) both presented their reddening values, and we adopted their mean values. For the star clusters for which Park & Lee (2007) and San Roman et al. (2009) did not present their reddening values, we adopted a uniform value of $E(B-V) = 0.1$ typical of the published values for the line-of-sight reddenings in M33 adopted by Sarajedini & Mancone (2007). Figure 7 shows the spatial distribution of these 523 star clusters. The large ellipse is the D_{25} boundary of the M33 disk (de Vaucouleurs et al. 1991). Figure 8 displays the integrated $M_V - (B-V)_0$ and $M_V - (V-I)_0$ CMDs of the sample star clusters of M33. The absolute magnitudes of the star clusters were derived for the adopted distance modulus of $(m-M)_0 = 24.64$ obtained by Galleti et al. (2004). The interstellar extinction curve, A_λ, is taken from Schlegel et al. (1998). Below each CMD in Figure 8 we plotted the star cluster distribution in color space. To the right of each CMD in Figure 8 we showed a histogram of the star clusters' absolute V magnitudes.

Sarajedini & Mancone (2007), Park & Lee (2007), and Paper I showed that the M33 star clusters are roughly separated into blue and red groups with a color boundary of $(B-V)_0 \simeq 0.5$ in the $M_V - (B-V)_0$ based on a small star cluster sample. However, this feature did not appear clearly in Figure 8 as in previous studies (Sarajedini & Mancone 2007; Park & Lee 2007; Paper I). Figure 8 shows that the star cluster luminosity function peaks near $M_V \sim -6.0$ mag, and nearly half of the star clusters appear between $M_V = -5.5$ and $M_V = -7.0$ mag.

By adding models to the CMDs, we can obtain a more detailed history of star cluster formation. Three fading lines (M_V as a function of age) from Bruzual & Charlot (2003) for a metallicity of $Z = 0.004$, $Y = 0.24$, which are thought to be appropriate for M33 star clusters (Chandar et al. 1999b) assuming a Salpeter initial mass function (IMF; Salpeter 1955) with lower and upper mass cutoffs of $m_L = 0.1\ M_\odot$ and $m_U = 100\ M_\odot$, and using the Padova-1994 evolutionary tracks, are plotted on the CMDs of M33 star clusters for three different total initial masses: 10^5, 10^4, and $10^3\ M_\odot$. The majority of the M33 star clusters fall between these three fading lines. From Figure 8, we note that none of the youngest clusters ($\sim 10^7$ yr) have masses approaching $10^5\ M_\odot$, which is consistent with the results of Chandar et al. (1999b) and Paper I. For ages older than 10^9 yr, some clusters with substantially higher masses are observed.

3.2. Color–Color Diagram

Figure 9 shows the integrated $(B-V)_0$ versus $(V-I)_0$ color–color diagram for M33 star clusters. Galactic globular

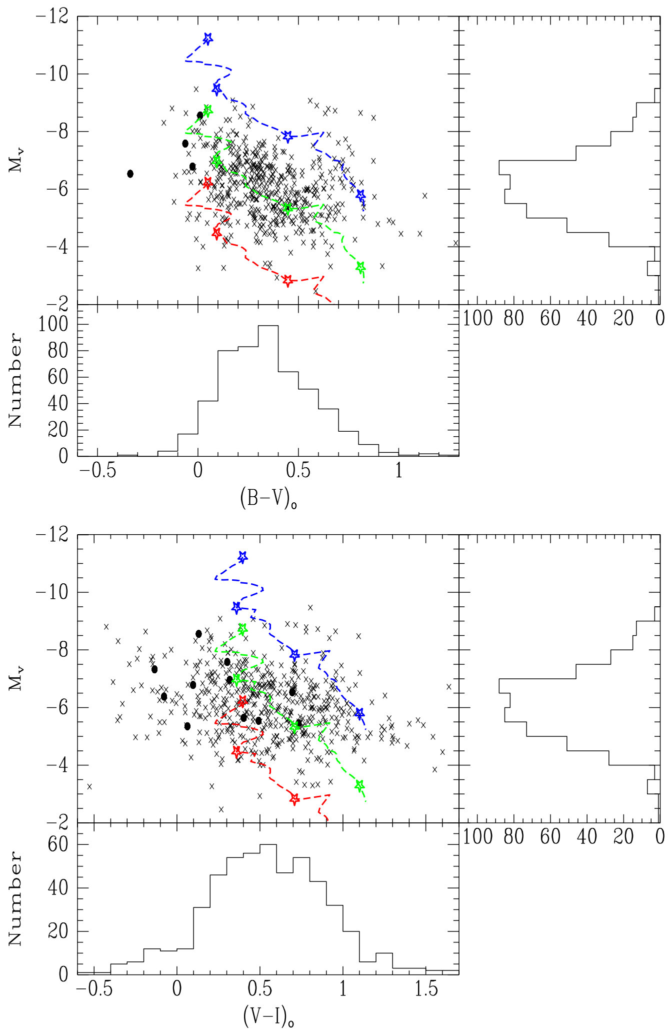

Figure 8. Color–magnitude diagrams of M33 clusters. Crosses represent the star clusters in Ma (2012) and this study; filled circles represent the star clusters in Park & Lee (2007), San Roman et al. (2009), and Zloczewski & Kaluzny (2009). Fading lines indicate star clusters with total initial masses of 10^5 (upper dashed line), 10^4, and 10^3 (lower dashed line) $M_\odot$, assuming a Salpeter IMF (see the text). Stars along each fading line represent ages of 10^7, 10^8, 10^9, and 10^{10} yr, from top to bottom, respectively.

clusters from the online database of Harris (1996; 2010 update) are also plotted for comparison. We overplotted the theoretical evolutionary path for the single stellar population (SSP; Bruzual & Charlot 2003) for $Z = 0.004$, $Y = 0.24$, which was appropriate for M33 (Chandar et al. 1999b). To identify different time periods, the different symbols correspond to 10^6, 10^7, 10^8, 10^9, and 10^{10} yr. For comparison, the evolutionary path of the SSP for $Z = 0.02$, $Y = 0.28$ is also overlaid.

In general, the star clusters in M33 are located along the sequence that is consistent with the theoretical evolutionary path for $Z = 0.004$, $Y = 0.24$, while some are on the redder or bluer side in the $(V - I)_0$ color. The wide color range of M33 star clusters implies a large range of ages, suggesting a prolonged epoch of formation. From Figure 9, we find that the photometry is shifted below the SSP lines, i.e., the sample star clusters are on the redder side in the $(B - V)_0$ color, when the star clusters have $(V - I)_0$ color between −0.5 and 0.4. In the same time, from Figure 9, we also find that the photometry for most of the Galactic globular clusters is also below the SSP lines but with much smaller range. The large scatter observed for M33 star

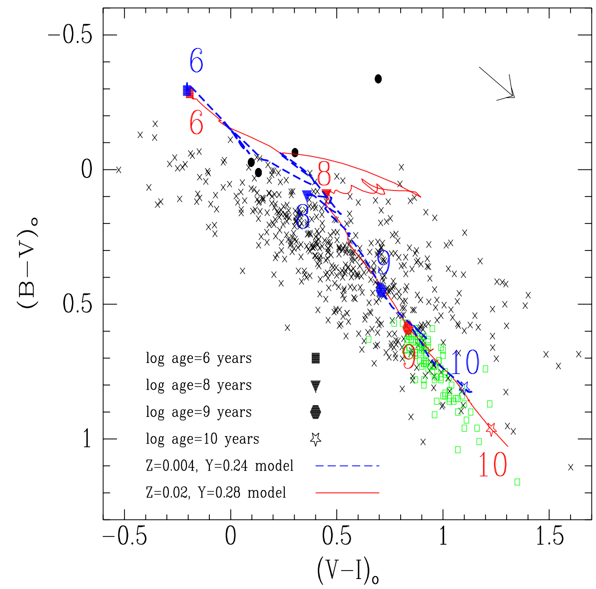

Figure 9. $(B - V)_0$ vs. $(V - I)_0$ color–color diagram of star clusters in M33. Crosses represent the star clusters in Ma (2012) and this study, while filled circles represent the star clusters in Park & Lee (2007), San Roman et al. (2009), and Zloczewski & Kaluzny (2009). Green squares are Galactic globular clusters from the online database of Harris (1996; 2010 update). Theoretical evolutionary paths from the SSP model (Bruzual & Charlot 2003) for $Z = 0.004$, $Y = 0.24$ (blue dashed line) and $Z = 0.02$, $Y = 0.28$ (red solid line) are drawn for every dex in age from 10^6 to 10^{10} yr. The arrow represents the reddening direction.

clusters possibly results from the large errors of the colors. By comparing with SSP models, we can see that there is a large range of ages of M33 star clusters, of which some star clusters are as old as the Galactic globular clusters.

4. SUMMARIES AND CONCLUSIONS

In this paper, we present *UBVRI* photometric measurements for 234 star clusters in the field of M33. These sample star clusters in M33 are from Park & Lee (2007), San Roman et al. (2009), and Zloczewski & Kaluzny (2009). For most of these star clusters, there is photometry in only two bands (*V* and *I*) in previous studies. Photometry of these star clusters is performed using archival images from LGGS (Massey et al. 2006). Detailed comparisons show that, in general, our photometry is consistent with previous measurements, and in particular, our photometry is in good agreement with that of Zloczewski & Kaluzny (2009). Combined with the star clusters' photometry in previous studies, we present the following results.

1. None of the M33 youngest clusters ($\sim 10^7$ yr) have masses approaching 10^5 $M_\odot$.
2. The wide color range of M33 star clusters implies a large range of ages, suggesting a prolonged epoch of formation. Comparisons with SSP models also suggest a large range of ages for M33 star clusters, and some as old as the Galactic globular clusters.

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