A CATALOG OF NEW M33 STAR CLUSTERS BASED ON HUBBLE SPACE TELESCOPE WFPC2 IMAGES

Won-Kee Park and Myung Gyoon Lee
Astronomy Program, Department of Physics and Astronomy, Seoul National University, Seoul 151-742, Korea;
wkpark@astro.snu.ac.kr, mglee@astrog.snu.ac.kr
Received 2007 June 15; accepted 2007 August 6

ABSTRACT

We present the results of a survey for star clusters in M33 using HST WFPC2 archive images. We have found 104 star clusters, including 32 new ones, in the images of 24 fields that were not included in previous studies. Combining these with previous data in the literature, we increase the number of M33 star clusters found in the HST images to 242. We have derived BVI integrated photometry of these star clusters from the CCD images taken with the CFH12k mosaic camera at the CFHT. Integrated color-magnitude diagrams of the M33 star clusters are found to be similar in general to those of star clusters in the Large Magellanic Cloud, except that M33 has a much lower fraction of blue star clusters. We find 29 red star clusters with \((B-V)_0 \leq 0.5\) and 71 star clusters with \((B-V)_0 \geq 0.5\). The luminosity function for the blue star clusters shows a peak at \(M_V \approx -7.3\) mag, while that for the intermediate-color star clusters shows a peak at the fainter magnitude \(M_V \approx -6.3\) mag. The luminosity function for the red star clusters also shows a peak at \(M_V \approx -6.8\) mag, although the number of clusters is small.

Key words: galaxies: clusters: general — galaxies: individual (M33) — galaxies: photometry — galaxies: star clusters

Online material: color figures, machine-readable tables

1. INTRODUCTION

Star clusters are an important tool for understanding the formation and evolution of a galaxy. Being aggregates of many stars, they are bright enough to be observed at great distances. They span a very broad range of age, from a few megayears to more than 10 Gyr, encapsulating the whole history of a galaxy. The age distribution of star clusters in a galaxy tells us about the formation and destruction history of the clusters, as well as about the evolution of the galaxy. The spatial distribution of star clusters delineates the structure of a galaxy, and their velocity distribution reveals the kinematics of the stellar population and the mass of the host galaxy.

Recent studies of star clusters in nearby late-type galaxies have revealed details of the clusters, showing that the populations among different galaxies are diverse (see Lee 2006 and references therein). Local Group galaxies in the nearby universe are ideal targets, due to their proximity, for studying in detail the properties of star clusters. There are three spiral galaxies in the Local Group: our Galaxy, M31, and M33. While star clusters in our Galaxy and M31 have been extensively studied, the star clusters in M33 have received relatively less attention.

M33 (NGC 598), the Triangulum galaxy, is a late-type spiral galaxy (Scd). It is located ~910 kpc from us (Kim et al. 2002). Its large angular size and inclination of \(i = 56^\circ\) (Zaritsky et al. 1989) make it particularly suitable for studies of its stellar contents. Its mass, \(M \sim 5 \times 10^{10} M_\odot\) (Corbelli 2003), falls in the intermediate range among the Local Group galaxies.

Surveys for star clusters in M33 have been rather sporadic. Early photometric surveys by Hiltner (1960) and Kron & Mayall (1960) identified about 25 star cluster candidates. Melnick & D’Odorico (1978) reported the discovery of 58 possible star cluster candidates, including most of the objects studied by Hiltner (1960). Christian & Schommer (1982) presented the most comprehensive catalog of 250 nonstellar objects in M33, including BVRI photometry of 60 star cluster candidates. Later, Christian & Schommer (1988) presented BV photometry for 71 additional star cluster candidates. All these surveys were based on photographic plates, so they 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 BVI images from the DIRECT project (Kalluzny et al. 1998; Stanek et al. 1998). They presented a list of 51 globular cluster candidates. While they covered the central region of M33, which previous surveys could not examine in detail, their survey was limited to bright star clusters of \(V \leq 19\) mag and did not cover the entire area of M33.

The Hubble Space Telescope (HST) offers a great advantage over ground-based telescopes for star cluster surveys in M33. At the distance of M33, star clusters can be easily identified by other extended sources, such as a background galaxy or an H ii region. Chandar et al. (1999a, 2001) searched for star clusters in M33 with HST data for the first time. They reported the discovery of 162 star clusters, including 131 previously unknown ones, in the 55 fields of HST WFPC2 images. Recently, Bedin et al. (2005) found 33 star clusters and 51 possible candidates from the F775W (I) image of one HST ACS field. Sarajedini et al. (2007) also reported a discovery of 24 star
clusters, including 11 new ones, from the VI images of two HST ACS fields in M33.

However, the areas of M33 covered by the previous HST-based surveys are much smaller than the entire area of M33. Therefore, it is necessary to increase the number of HST fields to make as complete a sample of star clusters as possible. The sample of star clusters established from the HST images also serves as a template for ground-based star cluster surveys.

We searched for new M33 star clusters using the additional HST WFPC2 images that became available after Chandar et al.'s (2001) work. We combined our result with previous M33 star cluster catalogs based on the HST images (Chandar et al. 1999a, 2001; Bedin et al. 2005; Sarajedini et al. 2007) and obtained homogeneous BVI photometry for the star clusters from the deep CCD imaging data taken at the Canada-France-Hawaii Telescope (CFHT) (W.-K. Park et al. 2008, in preparation).

In this paper we present the results of an M33 star cluster survey with the HST WFPC2 images. Throughout this paper we refer to the star clusters from the catalog of Bedin et al. (2005) with the designation “B” and those from Chandar et al. (1999a, 2001) with “CBF.” The designation “CS” means the star clusters from Christian & Schommer (1982, 1988). The designation “MKKSS” means those from Mocchi et al. (1998), and “MD” means those from Melnick & D’Odorico (1978). Finally, the designation “SBGHS” means the star clusters from Sarajedini et al. (2007).

The paper is composed as follows. Section 2 describes the HST WFPC2 and CFHT data used in this study, as well as the star cluster search method and integrated photometry procedures on CFHT images. Section 3 presents various properties of the star clusters: color-magnitude diagrams (CMDs), color-color diagrams...
(CCDs), and the spatial distribution of the star clusters. Finally, a summary and conclusion are given in the last section.

2. CLUSTER SELECTION AND PHOTOMETRY

2.1. Cluster Selection

We used WFPC2 images of M33 in the HST archive that were not used in the previous studies by Chandar et al. (1999a, 2001). The images were obtained using various filter combinations of F300W, F336W (U), F436W (B), F555W, F606W (V), and F814W (I). We selected only images with exposure times longer than 100 s in either V or I. The number of fields selected is 24, as listed in Table 1. The locations of the fields are displayed in Figure 1, along with the locations of the HST WFPC2 fields for previous star cluster surveys (Chandar et al. 1999a, 2001). Nine of our fields partially overlap previous survey regions. HST WFPC2 image sets used by Chandar et al. (1999a, 2001) were also downloaded from the archive, and images of previously known star clusters on these image sets were utilized as references for the visual search on the new image sets.

Bright star clusters in M33 are easily resolved on the HST WFPC2 images, so we selected star clusters using visual inspection of each image. We considered extended objects with a hint of resolved stars as star clusters.

Since the HST WFPC2 image sets used in this study have different depths, and they cover different environments in M33 with different filters, we could not put a completeness limit on the survey for each image. The detection of star clusters depends not only on their brightness but also on their sizes, morphologies, and environments. Experience from the visual investigation tells us that star clusters with $V \leq 20$ can be identified in the shallowest images of the current HST WFPC2 image sets.

From the investigation of HST WFPC2 fields, we have found 104 star clusters, 32 of which are new. The 32 new star clusters are listed in Table 2, and their V-band gray-scale images are shown in Figure 2. During the investigation, we identified eight CBF star clusters that were redundantly identified and registered under two different IDs: CBF-15 (CBF-45), CBF-20 (CBF-126), CBF-22 (CBF-91), CBF-53 (CBF-87), CBF-54 (CBF-85), CBF-56 (CBF-156), CBF-59 (CBF-95), and CBF-60 (CBF-94). The two star clusters in each pair not only have similar coordinates, but also similar V magnitudes with differences <0.2 mag. We carefully inspected the HST WFPC2 images of the regions where the eight pairs are located, and we found neither two star clusters of similar
magnitudes in the regions nor any possible substructures (i.e., multiple OB groups in a cluster) in the clusters that Chandar et al. (1999a, 2001) might have recognized as two separate star clusters. Therefore, we regard these eight cases as redundant identifications of the same star cluster. Throughout this paper, we present the total number of CBF samples as 154 instead of 162. From these 154 CBF samples, we identified 45 star clusters on our image sets.

One of our fields partially overlaps the region where Bedin et al. (2005) searched for star clusters with an HST ACS image and found 33 star clusters and 51 star cluster candidates. Fourteen star clusters and 18 star cluster candidates fall on our HST WFPC2 image. We could identify 13 star clusters, except cluster 15 in Bedin et al.’s (2005) list, which seems to be too faint to be seen in our F606W image. We also inspected the 18 star cluster candidates in our image. However, they are so compact in size that it was impossible to tell whether they are star clusters, except for cluster 83 in Bedin et al.’s (2005) list. We classified this one as a star cluster after careful inspection of the image.

In addition, we found that 12 star cluster candidates from previous ground-based surveys (Christian & Schommer 1982; Mochejska et al. 1998; Melnick & D’Odorico 1978) are real star clusters. The coordinates, photometric properties, and cross-identifications among the various studies for these 71 previously known clusters are listed in Table 3.

We have made a catalog of 242 star clusters in M33, combining our results with the previous results from HST-based surveys (Chandar et al. 1999a, 2001; Bedin et al. 2005; Sarajedini et al. 2007). It is the largest catalog of M33 star clusters available to date which includes only star clusters confirmed in HST images. It consists of 32 newly found star clusters from this study, 12 previous star cluster candidates that were confirmed to be genuine in
this study, 154 star clusters from Chandar et al. (1999a, 2001), 32 out of 33 star clusters in Bedin et al. (2005), 1 star cluster from the star cluster candidate list of Bedin et al. (2005), and 11 new star clusters from the list of Sarajedini et al. (2007). The positions and photometry of all the M33 star clusters not included in Tables 2 and 3 are listed in Table 4.

### 2.2. Photometry

All the star clusters in the combined catalog were observed with HST in different conditions with different purposes. The combination of filters used for the HST observations varies depending on the field. To secure homogeneous photometry data for all clusters, we used the integrated photometry of these clusters derived from the ground-based images given in W.-K. Park et al. (2008, in preparation) instead of deriving the photometry from the HST images. W.-K. Park et al. (2008, in preparation) present BVJ integrated aperture fluxes of clusters and cluster candidates in a 50′ × 80′ field of M33 based on CCD images taken with the CFH12k mosaic camera at the CFHT. The typical seeing of the data is ~0.9″ for all filters, and point sources of V ~ 23 are measured with errors smaller than 0.1. Details of the photometry are given in W.-K. Park et al. (2008, in preparation), and we give a brief description here.

Examination of an aperture growth curve of isolated bright clusters in the CFH12k CCD images indicates that most of the star cluster light is contained within an aperture of r ~ 4″. However, using such an aperture would cause a large scatter in the measurement of some clusters, because star clusters are often located in crowded fields in M33 so that some neighbor objects happen to be inside the same aperture. For this reason, we used an aperture of r = 2″ for the measurement of color, although an aperture of r = 4″ was used for V magnitude measurement to measure the total light of the star clusters. Some of the star clusters we missed happened to fall on the gaps between the chips in the mosaic camera, and some of them happened to be located in so crowded a region that we could not derive their photometry from the CFHT images.

### Table 3

| ID      | R.A. (J2000.0) | Decl. (J2000.0) | V^a  | B - V^b | V - J^b | E(B - V)^c | Cross-Identification^d |
|---------|----------------|----------------|------|---------|---------|------------|------------------------|
| 33...... | 01 32 34.45    | 30 37 42.09    | 20.18 ± 0.019 | 0.559 ± 0.016 | 0.725 ± 0.020 | 0.05 | CBF-143       |
| 34...... | 01 33 22.12    | 30 40 26.15    | 18.099 ± 0.010 | 0.080 ± 0.007 | 0.360 ± 0.014 | 0.10 | CBF-59        |
| 35...... | 01 33 22.26    | 30 40 59.64    | 18.663 ± 0.017 | ... | 0.475 ± 0.018 | 0.10 | CBF-60        |
| 36...... | 01 33 22.35    | 30 30 14.67    | 17.378 ± 0.004 | 0.130 ± 0.002 | 0.460 ± 0.004 | 0.10 | CBF-96        |
| 37...... | 01 33 23.84    | 30 30 26.18    | 19.480 ± 0.040 | 0.177 ± 0.026 | 0.685 ± 0.041 | 0.10 | CS-U126, MKKSS-5 |
| 38...... | 01 33 24.81    | 30 33 55.25    | 20.429 ± 0.077 | −0.117 ± 0.032 | 0.358 ± 0.068 | 0.10 | CBF-18        |
| 39...... | 01 33 25.60    | 30 29 57.03    | 18.179 ± 0.006 | 0.852 ± 0.005 | 1.115 ± 0.004 | 0.10 | CS-U126, MKKSS-5 |
| 40...... | 01 33 25.96    | 30 36 24.58    | 17.525 ± 0.007 | 0.265 ± 0.005 | 0.610 ± 0.007 | 0.10 | MKKSS-6        |
| 41...... | 01 33 26.34    | 30 41 06.96    | 18.099 ± 0.021 | 0.477 ± 0.014 | 1.043 ± 0.016 | 0.20 | CBF-92        |
| 42...... | 01 33 26.64    | 30 41 11.84    | 19.358 ± 0.028 | 0.361 ± 0.022 | 0.786 ± 0.031 | 0.20 | CBF-93        |

Notes.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Table 3 is published in its entirety in the electronic edition of the Astronomical Journal. A portion is shown here for guidance regarding its form and content.

### Table 4

| ID      | R.A. (J2000.0) | Decl. (J2000.0) | V^a  | B - V^b | V - J^b | E(B - V)^c | Cross-Identification^d |
|---------|----------------|----------------|------|---------|---------|------------|------------------------|
| 105...... | 01 32 38.83    | 30 39 17.77    | 19.942 ± 0.065 | 0.267 ± 0.090 | ... | 0.10 | CBF-162       |
| 106...... | 01 32 44.28    | 30 40 12.25    | 18.434 ± 0.005 | 0.749 ± 0.006 | 1.065 ± 0.006 | 0.10 | CBF-161, CS-U88 |
| 107...... | 01 33 01.16    | 30 35 44.65    | 19.485 ± 0.026 | 0.449 ± 0.029 | 1.152 ± 0.028 | 0.05 | CBF-39        |
| 108...... | 01 33 02.39    | 30 34 44.16    | 18.022 ± 0.006 | −0.034 ± 0.004 | 0.082 ± 0.011 | 0.15 | CBF-40        |
| 109...... | 01 33 08.10    | 30 28 00.12    | 19.062 ± 0.015 | 0.638 ± 0.011 | 0.822 ± 0.013 | 0.15 | CBF-86, CS-U140 |
| 110...... | 01 33 10.08    | 30 29 56.51    | 18.523 ± 0.022 | 0.296 ± 0.016 | 0.483 ± 0.018 | 0.15 | CBF-89        |
| 111...... | 01 33 13.84    | 30 29 05.27    | 18.884 ± 0.013 | 0.837 ± 0.014 | 0.999 ± 0.015 | 0.20 | CBF-53        |
| 112...... | 01 33 13.88    | 30 29 44.87    | 17.929 ± 0.012 | 0.042 ± 0.013 | −0.069 ± 0.018 | 0.15 | CBF-88        |
| 113...... | 01 33 14.28    | 30 28 22.78    | 18.298 ± 0.006 | 0.874 ± 0.005 | 1.109 ± 0.004 | 0.10 | CBF-54, CS-U137, MD-8 |
| 114...... | 01 33 15.15    | 30 32 53.26    | 19.714 ± 0.026 | 0.629 ± 0.018 | 0.856 ± 0.018 | 0.05 | CBF-144       |

Notes.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Table 4 is published in its entirety in the electronic edition of the Astronomical Journal. A portion is shown here for guidance regarding its form and content.

- Measured on CFH12k CCD image with r = 4.0″ aperture.
- Measured on CFH12k CCD image with r = 2.0″ aperture.
- Measured with UBVRI PSF photometry data by Massey et al. (2006). The uncertainties of the values are 0.05.
- B identifications are from Bedin et al. (2005), CBF identifications from Chandar et al. (1999a, 2001), CS identifications from Christian & Schommer (1982), MKKSS identifications from Mochejska et al. (1998), MD identifications from Melnick & D’Odorico (1978) based on the coordinates given by Ma et al. (2002), and SBGHS identifications from Sarajedini et al. (2007).
- Measured on HST WFC2 image instead of CFH12k CCD image, with r = 2.2″ and 1.0″ apertures for V and color measurement, respectively.
To supplement the photometry data for star clusters that could not be measured with CFH12k data, aperture photometry was carried out on the HST WFPC2 images. We did photometry on the fields that were observed with more than two filters, since instrumental magnitude cannot be converted to a standard system without color information. For most of the fields, two HST WFPC2 images of identical pointings exist per filter. Fields observed with only one exposure were not included in the measurement. Two images were combined with the combine task in IRAF\(^1\) with the creject option to remove the cosmic rays. Cosmetic defects were masked with the data quality images that accompany the scientific images. The centers of the clusters were determined visually with the IRAF imexam task. Then the IRAF phot task was used to measure the instrumental magnitudes of star clusters on the combined images. To be consistent with previous HST-based studies (Chandar et al. 1999a, 2001; Sarajedini et al. 2007), an aperture of \( r = 2.2'' \) was adopted for the magnitude measurement, while an aperture of \( r = 1.0'' \) was adopted for the color measurement. Local median values were measured as sky background level in an annulus of an inner radius of \( r = 3.5'' \) and outer radius of \( r = 5.0'' \) around each star cluster. The CTE correction was applied to the instrumental magnitudes according to the prescription given at A. E. Dolphin’s Web site.\(^2\) However, we did not correct for the geometric distortions in the WFPC2 CCD. The instrumental magnitudes were converted to a standard system using a relation found at the same Web site iteratively. In the end, we derived the photometry of 227 out of 242 star clusters with both CFH12k and HST WFPC2 images.

We compared our photometry of the clusters with previous photometry. There are 154 clusters in common with Chandar et al. (1999a, 2001), 16 clusters in common with Christian & Schommer (1982), 12 clusters in common with Mochejska et al. (1998), and 11 clusters in common with Sarajedini et al. (2007). Note that all photometry was carried out with different aperture sizes: Chandar et al. (1999a, 2001) and Sarajedini et al. (2007) used a nominal aperture of \( r = 2.2'' \) for magnitude measurement, while Christian & Schommer (1982, 1988) used apertures of \( r = 2.4'' \) and \( 3.7'' \), respectively. Mochejska et al. (1998) used an aperture of \( r = 2.88'' \). However, aperture sizes in all cases were chosen to contain the light from a star cluster as much as possible, so the resulting aperture magnitude for each star cluster should be more or less the same.

Figure 3 shows the comparison of our photometry of the clusters with previous photometry. Large scatter makes it difficult to see the difference in magnitude, but for bright star clusters \((V \leq 19)\), there is little magnitude difference between this and other studies: \( \Delta V = -0.04 \) with \( \sigma = 0.19 \) (this study minus Chandar et al. 1999a, 2001), \( \Delta V = -0.04 \) with \( \sigma = 0.17 \) (this study minus Mochejska et al. 1998), \( \Delta V = 0.00 \) with \( \sigma = 0.10 \) (this study minus Christian & Schommer 1982, 1988), and \( \Delta V = -0.04 \) with \( \sigma = 0.12 \) (this study minus Sarajedini et al. 2007). For fainter sources, however, our measurements get systematically fainter than the other space-based measurements. Given that most of the star clusters are located in the region near the M33 center where crowding is severe and sky varies significantly, the sky background level is likely to be overestimated in ground-based images due to the unresolved faint stars, which would lead to a fainter estimation of source brightness.

Both the \((B - V)\) and \((V - I)\) colors show good agreement with all the previous studies down to the faintest magnitude in our samples. The differences between this study and other photometry are \( \Delta(B - V) = -0.05 \) with \( \sigma = 0.20 \) (this study minus Chandar et al. 1999a, 2001), \( \Delta(V - I) = -0.01 \) with \( \sigma = 0.10 \) (this study minus Chandar et al. 1999a, 2001), \( \Delta(B - V) = 0.06 \) with \( \sigma = 0.10 \) (this study minus Mochejska et al. 1998), \( \Delta(V - I) = 0.08 \) with \( \sigma = 0.22 \) (this study minus Mochejska et al. 1998), \( \Delta(B - V) = 0.04 \) with \( \sigma = 0.08 \) (this study minus Christian & Schommer 1982, 1988), and \( \Delta(V - I) = -0.04 \) with \( \sigma = 0.08 \) (this study minus Sarajedini et al. 2007). The only exception to this tendency is the \((V - I)\) difference between our study and those of Christian & Schommer (1982, 1988), which turned out to be \( \Delta(V - I) = -0.16 \) with \( \sigma = 0.10 \) (this study minus Christian & Schommer 1982, 1988).

### 2.3. Reddening

To get the intrinsic color of the star clusters, the photometric measurements must be corrected for reddening. We estimated the foreground reddening for each star cluster using the \((U - B)\) - \((B - V)\) diagram for early-type stars in the field covering the cluster. We used the \(UBVRI\) photometry of stars in the area of M33 covered in the Local Group survey performed by Massey et al. (2006). The \(E(B - V)\) derived for each cluster is listed in the seventh column of Tables 2–4.

The \(E(B - V)\) values we derived for the M33 star clusters range from \(-0.05\) to \(-0.20\). For about 130 star clusters, the value of \(E(B - V)\) turned out to be \(0.1\), and for about 100 star clusters the values of \(E(B - V)\) were found to be \(\geq 0.15\). Chandar et al. (1999b) obtained \(E(B - V)\) toward their 60 star clusters either from the photometry of neighboring individual stars by applying reddening-free parameters or by using \(E(B - V)\) values from Massey et al. (1995). The \(E(B - V)\) values are in the range \(0.06-0.33\), and most of them are found to be \(-0.10\). Sarajedini et al. (2000) also derived reddening for their 10 globular cluster samples from the shapes of the red giant branches in the CMDs of

---

\(^1\) IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

\(^2\) See http://purcell.as.arizona.edu/wfpc2_calib/.
resolved stars. Their $E(V - I)$ estimates are below 0.1, except for $E(V - I) = 0.25 \pm 0.03$ for cluster 131 (CS-H10). Sarajedini et al. (2007) also obtained $E(V - I)$ for 17 star clusters in the same way as Sarajedini et al. (2000), ranging from 0.10 to 0.45.

Since our error in $E(B - V)$ measurement is as large as $\pm 0.05$, it is quite difficult to see the consistency between our results and other results. But the fact that the $E(B - V)$ distribution shows a peak at $E(B - V) \sim 0.10$, a typical value found in previous studies (Chandar et al. 1999b), indicates that the results obtained in this study are in general consistent with previous studies.

3. RESULT

3.1. Color-Magnitude Diagram

Figure 4 displays the integrated $M_V - (B - V)_0$ and $M_V - (V - I)_0$ CMDs of the star clusters in M33. The absolute magnitudes of the star clusters were derived for the adopted distance modulus of $(m - M)_0 = 24.8$ (Kim et al. 2002) and the visual extinction–to–reddening ratio $R_V = 3.11$ (Schlegel et al. 1998). For comparison, we display the CMDs for the star clusters in the LMC (Bica et al. 1996) in Figure 4c and the CMDs for the open clusters (Lata et al. 2002) and globular clusters (Harris 1996) in our Galaxy. Globular clusters are marked with squares in both panels. Histograms in all panels show the normalized distributions of colors for star cluster samples plotted in each panel. [See the electronic edition of the Journal for a color version of this figure.]

Fig. 4.—Integrated CMDs of the star clusters in M33, the LMC, and our Galaxy. (a) $M_V - (B - V)_0$ CMD and (b) $M_V - (V - I)_0$ CMD of M33 star clusters. In both panels, filled circles denote the star clusters newly discovered in this study, and open circles denote the previously known star clusters that were confirmed in this study. Squares denote the star clusters from Sarajedini et al. (2007), crosses those in the list of Chandar et al. (1999a, 2001), and triangles those from Bedin et al. (2005). (c) Integrated $M_V - (B - V)_0$ CMD of star clusters in the LMC (Bica et al. 1996). (d) Integrated $M_V - (B - V)_0$ CMD of open clusters (Lata et al. 2002) and globular clusters (Harris 1996) in our Galaxy. Globular clusters are marked with squares in both panels. Histograms in all panels show the normalized distributions of colors for star cluster samples plotted in each panel. [See the electronic edition of the Journal for a color version of this figure.]
only a small number of red clusters with \((B-V)_h > 0.5\) in M33. The \((B-V)_h\) color range of the red clusters in M33, \(0.5 < (B-V)_h < 1.1\), is similar to that for Galactic globular clusters but much larger than that for LMC red clusters, \(0.5 < (B-V)_h < 0.8\). We found only one new red cluster and confirmed two known red clusters. Cluster 85 (cluster 27 in Mochejska et al. 1998), one of the two red clusters confirmed in this study, happens to be the brightest \([M_V = -9.070\) and \((B-V)_h = 0.575]\) among the known red clusters in M33. The reddest cluster is cluster 89, which has integrated colors \((B-V)_h = 1.579\) and \((V-I)_h = 1.810\).

It is interesting to note that there are only a few red star clusters that are fainter than \(M_V \sim -6.0\) in M33, while there are many such faint red star clusters seen in the LMC. The lack of faint red clusters in our catalog of M33 clusters may be due to incompleteness of our cluster search or may be an intrinsic feature of the M33 star cluster system. While we selected HST WFPC2 images on the basis of \(V \) or \(I\) exposure times, many of the resulting image sets were obtained with combinations of \(V\) and shorter wavelength passbands such as \(U\) and \(B\), rather than combinations of \(V\) and \(I\). So there is a possibility that our star cluster detection might have been biased toward blue star clusters. However, it may be an intrinsic feature, considering that Chandar et al. (2001) already showed that M33 red star clusters with \((V-I)_h > 0.78\) have lognormal-type luminosity functions (LFs), while intermediate-color clusters with \((V-I)_h \leq 0.78\) show no turnover down to the completeness limit in their LFs.

3.2. Color-Color Diagram

Figure 5 shows the integrated \((B-V)_h\) vs \((V-I)_h\) CCD of the M33 star clusters, along with their \((B-V)_h\) and \((V-I)_h\) histograms. Galactic globular clusters are also plotted for comparison. We overlaid the theoretical evolutionary path for the single stellar population (SSP; Bruzual & Charlot 2003) for \(Z = 0.004, Y = 0.24\) that was reported to give the best overall fit to their M33 star cluster samples younger than log \(t \leq 9.0\) (Chandar et al. 1999b). For comparison, the evolutionary path of the SSP for \(Z = 0.02, Y = 0.28\) is also overlaid.

Most of the new clusters in M33, including those from Bedin et al. (2005), are located along the sequence that is consistent with the theoretical evolutionary path for \(Z = 0.004, Y = 0.24\), while a few of them are on the redder side in the \((V-I)_h\) color. This is similar to the case of previously known clusters in M33, as well as the star clusters in M51 (Hwang & Lee 2007). Some bright clusters among these redder clusters are consistent with the theoretical evolutionary path for \(Z = 0.02, Y = 0.28\). However, the rest cannot be explained with any other models. The continuous distribution of star clusters along the model line indicates that M33 star clusters have been formed continuously from the epoch of the first star cluster formation until recent times.

The \((V-I)_h\) distribution shows only one peak at \(0.45\) and monotonically decreases toward the red end, while the \((B-V)_h\) distribution shows two distinct peaks at \(~0.15\) and \(~0.55\). The \((B-V)_h\) distribution is similar to that given by Sarajedini & Mancone (2007), except that the red peak at \((B-V)_h \approx 0.55\) in our result is 0.1 bluer than their result, \((B-V)_h \approx 0.65\). The blue peak corresponds to the age of \(~2 \times 10^7\) yr and the red peak to the age of \(~1 \times 10^7\) yr, if we assume the metallicity of the star clusters to be \(Z = 0.004\).

Based on the integrated photometry of the clusters, we can select old globular cluster candidates from our catalog. The \((B-V)_h\) color distribution shows that the blue end of the red star cluster population is located at \((B-V)_h \sim 0.5\), which is similar to that of Galactic globular clusters. Although we do not see a similar red peak in the \((V-I)_h\) color distribution of the M33 star clusters, it is reasonable to set the color criterion for \((V-I)_h\) color as well, in accordance with the \((V-I)_h\) distribution of Galactic globular clusters. The color ranges for most of the Galactic globular clusters in Figure 5 are \(0.5 < (B-V)_h < 1.1\) and \(0.7 < (V-I)_h \leq 1.2\). There are 29 star clusters with this color range in our catalog that are old globular cluster candidates in M33. Ten of them are newly found in this study. The globular cluster candidates are listed in Table 5, along with their integrated photometry and cross-identifications with previous catalogs.

Nine out of 10 globular clusters in Sarajedini et al. (2000) satisfy our color selection criterion. One globular cluster, C38 in Christian & Schommer (1982; CBF-114), is not included because its color \((V-I)_h = 0.684\) is a little bluer than the blue limit of the criterion. Our list of 29 globular cluster candidates also includes the three oldest star clusters in the list of Sarajedini et al. (2007)—clusters 58, 131, and 228—which are all estimated to be older than log \(t \sim 9.8\).

3.3. Spatial Distribution

We divided the M33 star cluster sample into three groups according to their \((B-V)_h\) color for further analysis: blue star clusters with \((B-V)_h \leq 0.3\), intermediate-color star clusters with \(0.3 < (B-V)_h < 0.5\), and red star clusters with \((B-V)_h \geq 0.5\). Figure 6 displays the spatial distribution of each color group. We also plotted for comparison the locations of H ii regions (Hodge et al. 1999) that trace well the spiral arm structures of M33. Since HST WFPC2 observations covered in our catalog do not cover the entire area of M33, the spatial distribution of star clusters cannot be used for the study of the spatial structure of the M33 cluster.
system. Figure 6 shows that relatively more red clusters are found in the outer region of M33 than blue and intermediate-color clusters, and that many of the blue stars are located in H II regions.

Note that the regions investigated in this study include three fields far to the east of the M33 center (see Fig. 1 for the locations of these fields). Had any star clusters been found in these regions, it would have given us a clue as to the extent of the star cluster system in M33. However, no star clusters were found in these regions with our image sets.

3.4. Cluster Luminosity Function

With the largest sample of star clusters available, we derived the LFs of the star clusters, displaying them in Figure 7a. Although we did not estimate the completeness of our survey, it appears that it is reasonably complete for clusters brighter than $V \leq 19$. Therefore, only the bright part of the LF is considered in further discussion.

In Figure 7a the LF for the blue star clusters shows a peak at $M_V \approx -7.3$ mag and decreases as the magnitude gets fainter, while the intermediate-color star LF shows a peak at the fainter magnitude $M_V \approx -6.3$ mag. The LF for the red star clusters also shows a peak at $M_V \approx -6.8$ mag, although the number of clusters is small.

We fitted the LFs for $V < 19$ mag using a single Gaussian function, obtaining $M_V(\text{peak}) = -6.90 \pm 0.04$ mag and $\sigma(M_V) = 1.96$ for the blue star clusters, $M_V(\text{peak}) = -6.34 \pm 0.05$ mag and $\sigma(M_V) = 1.53$ for the intermediate-color star clusters, and $M_V(\text{peak}) = -6.79 \pm 0.06$ mag and $\sigma(M_V) = 1.39$ for the red star clusters.

Chandar et al. (2001) presented the LF of the M33 star clusters for two color groups: $0.70 < (V - I)_0 < 0.78$ (intermediate-color star clusters) and $0.78 < (V - I)_0$ (red star clusters). So we derived the cluster LFs for the same color groups, as shown in Figure 7b. We also plotted the cluster LFs given by Chandar et al. (2001) in Figure 7c for comparison. We adjusted the LFs given by Chandar et al. (2001) applying the same distance modulus for M33 [we adopted $(m - M)_0 = 24.80$, while Chandar et al. (2001) adopted $(m - M)_0 = 24.64$], shifting the magnitude bins of Chandar et al.’s (2001) LF 0.16 mag brighter.

In Figure 7b the LFs for the intermediate-color and red star clusters derived according to the $(V - I)_0$ color show peaks at $M_V \approx -6.8$ mag, which is roughly similar to those derived according to the $(B - V)_0$ color in Figure 7a. However, the LFs for the intermediate-color and red star clusters derived in this study are somewhat different from those given by Chandar et al. (2001) in Figure 7c. Our LFs contain a larger number of faint star clusters than given by Chandar et al. (2001). The peak magnitude in the LF for the red star clusters derived in this study is about 0.3 mag fainter than that of Chandar et al. (2001), $M_V \approx -7.1$ mag, while the peak magnitude in the LF for the intermediate-color star clusters in this study is similar to that of Chandar et al. (2001), $M_V \approx -6.7$ mag.
Chandar et al. (2001) sampled more bright star clusters than in our survey. Chandar et al. (2001) combined their catalog based on HST WFPC2 data with previous catalogs of M33 star clusters to increase the number of the sample for deriving the LFs. We used only star cluster samples obtained with HST observations. Previous ground-based surveys covered a wider area in M33 with shallower depth and poorer resolution compared with HST surveys so that they preferentially included a larger number of bright and large clusters than the HST surveys. For example, the blue LF for the Bedin et al. (2005) samples included in this study with \((B - V)_0 \leq 0.3\) has a peak at the same magnitude as that for blue samples displayed in Figure 7a. Thus, it is natural that our LFs include a higher portion of faint star clusters than those of Chandar et al. (2001).

4. SUMMARY AND CONCLUSION

We have carried out a survey of star clusters in M33 using the HST WFPC2 images in the HST archive that were not covered in previous studies. We have found 104 star clusters, including 32 new clusters and 12 known clusters confirmed in this study, from 24 fields of HST WFPC2 images. We combined 44 star clusters from this study, 154 star clusters from Chandar et al. (1999a, 2001), 33 star clusters from Bedin et al. (2005), and 11 star clusters from Sarajedini et al. (2007) to build a catalog of 242 star clusters. This is the most comprehensive catalog available to date which contains only confirmed genuine star clusters in M33. We present the integrated photometry of these star clusters derived from the \(BV/T\) images taken with the CFH12K CCD camera at the CFHT. The photometric properties of the star clusters are summarized as follows:

1. The integrated CMD of the star clusters shows that there are two distinct populations in M33: a large number of blue star clusters and a small number of red star clusters. The CMD of the M33 star clusters is in general similar to that of the LMC star clusters.

2. We divide the cluster sample into three groups according to \((B - V)_0\) color: blue star clusters with \((B - V)_0 \leq 0.3\), intermediate-color star clusters with \(0.3 < (B - V)_0 < 0.5\), and red star clusters with \((B - V)_0 \geq 0.5\). Most of the new clusters found or confirmed in this study are blue clusters. There are 29 old globular cluster candidates with \(0.5 < (B - V)_0 < 1.1\) and \(0.7 < (V - I)_0 < 1.2\), 10 of which are newly found in this study.

3. Most of the new clusters in M33 are located along the theoretical evolutionary path for \(Z = 0.004, Y = 0.24\) in the \((B - V)_0-(V - I)_0\) CCD, while a few of them are on the redder side in the \((V - I)_0\) color.

4. Relatively more red clusters are found in the outer region of M33 than blue and intermediate-color clusters, and many of the blue stars are located in H II regions.

5. The luminosity function (LF) for the blue star clusters shows a peak at \(M_V \approx -7.3\) mag, while the intermediate-color star cluster LF shows a peak at the fainter magnitude \(M_V \approx -6.3\) mag. The LF for the red star clusters also shows a peak at \(M_V \approx -6.8\), although the number of clusters is small.

Note added in manuscript.—It is found that a new cluster, cluster 21, was listed as an unclassified object, CS-U69, in Christian & Schommer (1982). Conor Mancone and Ata Sarajedini are thanked for pointing this out.

The authors thank Narae Hwang for many fruitful discussions and comments during the work in this study. This work was supported in part by the ABRL (R14-2002-058-01000-0). This work is based in part on W.-K. P.’s Ph.D. thesis at Seoul National University.
REFERENCES
Bedin, L. R., Piotto, G., Baume, G., Momany, Y., Carraro, G., Anderson, J., Messineo, M., & Ortolani, S. 2005, A&A, 444, 831
Bica, E., Claria, J. J., Dottori, H., Santos, J. F. C., Jr., & Piatti, A. E. 1996, ApJS, 102, 57
Bruzual, G., & Charlot, S. 2003, MNRAS, 344, 1000
Chandar, R., Bianchi, L., & Ford, H. C. 1999a, ApJS, 122, 431
———. 1999b, ApJ, 517, 668
———. 2001, A&A, 366, 498
Christian, C. A., & Schommer, R. A. 1982, ApJS, 49, 405
———. 1988, AJ, 95, 704
Corbelli, E. 2003, MNRAS, 342, 199
Harris, W. E. 1996, AJ, 112, 1487
Hiltner, W. A. 1960, ApJ, 131, 163
Hodge, P. W., Balsley, J., Wyder, T. K., & Skelton, B. P. 1999, PASP, 111, 685
Hwang, N., & Lee, M. G. 2007, AJ, submitted
Kaluzny, J., Stanek, K. Z., Krockenberger, M., Sasselov, D. D., Tonry, J. L., & Mateo, M. 1998, AJ, 115, 1016
Kim, M., Kim, E., Lee, M. G., Sarajedini, A., & Geisler, D. 2002, AJ, 123, 244
Kron, G. E., & Mayall, N. U. 1960, AJ, 65, 581
Lata, S., Pandey, A. K., Sagar, R., & Mohan, V. 2002, A&A, 388, 158
Lee, M. G. 2006, Bull. Astron. Soc. India, 34, 99
Ma, J., Zhou, X., Chen, J-S., Wu, H., Jiang, Z-J., Xue, S-J., & Zhu, J. 2002, Chinese J. Astron. Astrophys., 2, 197
Massey, P., Armandroff, T. E., Pyke, R., Patel, K., & Wilson, C. 1995, AJ, 110, 2715
Massey, P., Olsen, K. A. G., Hodge, P. W., Strong, S. B., Jacoby, G. H., Schlingman, W., & Smith, R. C. 2006, AJ, 131, 2478
Melnick, J., & D’Odorico, S. 1978, A&AS, 34, 249
Mochejska, B. J., Kaluzny, J., Krockenberger, M., Sasselov, D. D., & Stanek, K. Z. 1998, Acta Astron., 48, 455
Sarajedini, A., Barker, M. K., Geisler, D., Harding, P., & Schommer, R. 2007, AJ, 133, 290
Sarajedini, A., Geisler, D., Schommer, R., & Harding, P. 2000, AJ, 120, 2437
Sarajedini, A., & Mancone, C. L. 2007, AJ, 134, 447
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Stanek, K. Z., Kaluzny, J., Krockenberger, M., Sasselov, D. D., Tonry, J. L., & Mateo, M. 1998, AJ, 115, 1894
Zaritsky, D., Elston, R., & Hill, J. M. 1989, AJ, 97, 97