STAR CLUSTERS IN M33: UPDATED UBVRI PHOTOMETRY, AGES, METALLICITIES, AND MASSES

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ABSTRACT

The photometric characterization of M33 star clusters is far from complete. In this paper, we present homogeneous UBVRI photometry of 708 star clusters and cluster candidates in M33 based on archival images from the Local Group Galaxies Survey, which covers 0.8 deg^{2} along the galaxy’s major axis. Our photometry includes 387, 563, 616, 580, and 478 objects in the UBVRI bands, respectively, of which 276, 405, 430, 457, and 363 do not have previously published UBVRI photometry. Our photometry is consistent with previous measurements (where available) in all filters. We adopted Sloan Digital Sky Survey ugriz photometry for complementary purposes, as well as Two Micron All Sky Survey near-infrared JHK photometry where available. We fitted the spectral-energy distributions of 671 star clusters and candidates to derive their ages, metallicities, and masses based on the updated PARSEC simple stellar populations synthesis models. The results of our χ^{2} minimization routines show that only 205 of the 671 clusters (31%) are older than 2 Gyr, which represents a much smaller fraction of the cluster population than that in M31 (56%), suggesting that M33 is dominated by young star clusters (<1 Gyr). We investigate the mass distributions of the star clusters—both open and globular clusters—in M33, M31, the Milky Way, and the Large Magellanic Cloud. Their mean values are log(M_{cl}/M_{⊙}) = 4.25, 5.43, 2.72, and 4.18, respectively. The fraction of open to globular clusters is highest in the Milky Way and lowest in M31. Our comparisons of the cluster ages, masses, and metallicities show that our results are basically in agreement with previous studies (where objects in common are available); differences can be traced back to differences in the models adopted, the fitting methods used, and stochastic sampling effects.

Key words: catalogs – galaxies: individual (M33) – galaxies: star clusters: general – globular clusters: general

Online-only material: machine-readable tables

1. INTRODUCTION

Since star clusters represent an important component of the galaxies with which they are associated, studies of star clusters’ stellar populations and age distributions can provide clues to the formation and evolution of their host galaxies. In addition, since populous star clusters are much more luminous than individual stars, they are usually much easier to observe and study.

At a distance of 847 ± 60 kpc—equivalent to a distance modulus of (m − M)_{0} = 24.64 ± 0.15 mag (Galleti et al. 2004)—M33 (also known as the Triangulum Galaxy) is the third largest spiral galaxy in the Local Group of galaxies. Since the galaxy is seen relatively face-on, under an inclination of i = 56° ± 1° (Zaritsky et al. 1989), it is eminently suitable for studies of its star cluster system. At present, the most comprehensive and widely used star cluster catalog is that of Sarajedini & Mancone (2007), which combines data on almost all M33 star clusters published in the literature, including information on their photometry, ages, metallicities, and masses. The latest version of this catalog (henceforth SM10) includes 595 star clusters and candidates. Park & Lee (2007) found 104 star clusters in Hubble Space Telescope (HST)/Wide Field and Planetary Camera 2 (WFPC2) archival images, including 32 new objects based on new HST observations. Although their observations improved the spatial coverage of the M33 disk, this catalog is still incomplete for the entire disk. These authors found two different star cluster populations on the basis of their sample’s color–magnitude diagram (CMD), including a large number of blue clusters and a smaller number of red objects. They also suggested that relatively more red clusters are found in the galaxy’s outer regions.

Subsequently, Zloczewski et al. (2008) published a list of 4780 extended sources, including 3554 new cluster candidates observed with the MegaCam instrument on the 3.6 m Canada–France–Hawaii Telescope (CFHT). However, ~60% of these clusters are not considered genuine owing to possible misidentifications (San Roman et al. 2009, 2010). Based on HST/Advanced Camera for Surveys (ACS)–Wide Field Channel (WFC) observations, San Roman et al. (2009) presented photometry of 161 M33 star clusters, of which 115 were newly identified. Based on their CMDs, they suggested that these clusters’ ages were between 0.01 and 1 Gyr, whereas their masses range from 5\times10^{3} M_{⊙} to 5\times10^{4} M_{⊙}. However, these authors also point out that, since their photometry is generally not sufficiently deep to detect the main-sequence turnoff (MSTO), very few of their sample clusters are older than 1 Gyr. Using MegaCam on the CFHT, San Roman et al. (2010) identified 2990 extended sources in M33, 599 of which were new cluster candidates and 204 of which were previously known clusters. Based on CMD analysis, these authors suggested that the majority of the clusters have young to intermediate ages, although their sample also includes some old objects. They suggested that a possible M31–M33 interaction some 3.4 Gyr ago may have triggered an epoch of star (cluster) formation in M33.

Comparison of observational spectral-energy distributions (SEDs) with theoretical stellar population synthesis models by application of χ^{2} minimization is a widely used technique to estimate ages, metallicities, reddening values, and masses of...
extragalactic star clusters. This technique has been applied to the cluster systems in, e.g., M31 (Jiang et al. 2003; Fan et al. 2006, 2010; Ma et al. 2007, 2009; Wang et al. 2010), M33 (Ma et al. 2001, 2002a, 2002b, 2002c, 2004a, 2004b), the Large Magellanic Cloud (LMC; e.g., de Grijs & Anders 2006; Popescu et al. 2012; de Grijs et al. 2013), M82 (de Grijs et al. 2003b; Lim et al. 2013), NGC 3310, and 6745 (de Grijs et al. 2003a), as well as for stellar population synthesis model comparisons (de Grijs et al. 2005; Fan & de Grijs 2012).

In this paper, we first obtain photometry for all M33 star clusters in our sample (see Section 2.1 for definition) based on archival images from the Local Group Galaxies Survey (LGGS; Massey et al. 2006). Using photometry in the \textit{UBVRI}, \textit{ugriz} (Sloan Digital Sky Survey; SDSS) bands and Two Micron All Sky Survey (2MASS) \textit{JHK} magnitudes (Skrutskie et al. 2006)\(^5\) when available, the ages and masses of the star clusters in our sample are estimated by comparison of their observed SEDs with updated {\sc parsec} (version 1.1) isochrones (Bressan et al. 2012). This paper is organized as follows. Section 2 describes the sample selection and \textit{UBVRI} photometry. In Section 3.1 we describe the simple stellar population (SSP) models used as well as our method to estimate the cluster ages and metallicities. In Section 3.2 we present the clusters’ mass estimates, and we summarize and conclude the paper in Section 4.

2. DATA

2.1. Sample

Our sample star clusters are mainly selected from San Roman et al. (2010), whose database is based on observations with the CFHT/MegaCam camera. Their catalog covering the M33 area contains 2990 objects, including background galaxies, confirmed star clusters, and cluster candidates, as well as unknown objects. The catalog provides the positions and \textit{ugriz} photometry of all objects. Since our focus is on the star clusters, galaxies and unknown objects were eliminated from the catalog, and we subsequently performed photometry for the 803 star clusters and cluster candidates in their catalog.

We used archival \textit{UBVRI} images from the LGGS, which covers a region of 0.8 deg\(^2\) along the galaxy’s major axis. The images we used consisted of three separate but overlapping fields with a scale of 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 × 36 arcmin\(^2\). The observations were taken with the Kitt Peak National Observatory 4 m Telescope between 2000 August and 2002 September. The median seeing of the LGGS images is \(\sim 1′′\). Although Ma (2012) inspected the images and obtained \textit{UBVRI} photometry for all star clusters and unknown objects in Sarajedini & Mancone (2007) based on archival LGGS images, there are still hundreds of star clusters from San Roman et al. (2010) in this field which do not have published \textit{UBVRI} photometry. Therefore, here we only perform photometry of the clusters in the LGGS images following the identifications of San Roman et al. (2010). We employed the latest version of SExtractor\(^6\) (Bertin & Arnouts 1996) to find the sources in the images and match them to the coordinates of our 803 sample star clusters and candidates. Eventually, we detected 588 clusters and candidates with quality FLAGS = 0, which indicates that there are no problems associated with these objects (i.e., no contamination by nearby sources or saturation effects) in the LGGS images.

To supplement these data, we also include 120 confirmed star clusters from the updated (2010) version of Sarajedini & Mancone (2007, SM10), which were not included in San Roman et al. (2010). Thus, the number of clusters in our final sample is 708.

Figure 1 shows the spatial distribution of all sample clusters and candidates in the M33 field. The three data frames represent the field of view of the Massey et al. (2006) data, and the large square outline covers the observed field of San Roman et al. (2010). The combined total number of clusters and cluster candidates is 588. These latter clusters have been cross-identified in the Massey et al. (2006) image, which we will focus on here; we do not consider clusters outside of the boundaries of the Massey et al. (2006) image. The orange symbols represent the 120 star clusters identified by SM10 but not included in San Roman et al. (2010). It is clear that most star clusters and candidates are associated with and projected onto the galaxy’s disk (i.e., inside the galaxy’s \(D_{25}\)).

2.2. Integrated Photometry

Prior to this work, Massey et al. (2006) compiled point-spread-function photometry for 146,622 stars (point sources) in the M33 fields, with photometric uncertainties of <10% at \textit{UBVRI} \(\sim 23\) mag. However, there are no relevant discussions of the extended sources (e.g., star clusters and galaxies) in the published LGGS papers. Recently, Ma (2012) derived aperture photometry of 392 star clusters and unknown objects in the

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\(^{5}\) http://www.ipac.caltech.edu/2mass/

\(^{6}\) http://www.astromatic.net/software/sExtractor; version 2.8.6 was updated on 2009 October 5.
catalog of Sarajedini & Mancone (2007) in the $UBVRI$ bands. However, there are still several hundred M33 star clusters and cluster candidates identified by San Roman et al. (2010) which lack LGGS photometry in the $UBVRI$ bands.

To obtain additional photometric information for the star clusters, we carried out photometric measurements of our sample M33 clusters and candidates. SExtractor was applied to the LGGS images in all of the $UBVRI$ bands to derive supplementary and homogeneous photometry. The SExtractor code provides isophotal magnitudes corrected for the flux missed by isophotal-magnitude determination, MAG_ISO COR. This approach works well for stars but poorly for elliptical (galaxy) profiles with broader wings. SExtractor also delivers automatic aperture photometry measurements of galaxies based on the first-moment algorithm of Kron (1980), MAG_AUTO. The MAG_BEST magnitudes can be automatically mapped onto MAG_AUTO if neighbors do not bias the photometry by more than 10%. In all other cases, MAG_BEST is set to equal MAG_ISO COR, because the latter measurements are not significantly affected by nearby sources. Thus, we adopted the MAG_BEST magnitudes as our final instrumental magnitudes. As a consequence, we do not need to choose the size of the aperture used. The instrumental magnitudes were calibrated in the standard Johnson–Kron–Cousins $UBVRI$ system by comparing the published magnitudes of stars from Massey et al. (2006), who calibrated their photometry using Landolt (1992) standard stars, 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. The calibration errors range from $\sim0.01$ to $\sim0.03$ mag in the $UBVRI$ bands, with more than 300 secondary standard stars available in each field. Finally, we obtained photometry for 708 objects, with 387, 563, 616, 580, and 478 sources in the individual $UBVRI$ bands, respectively, of which 276, 405, 430, 457, and 363 star clusters and candidates do not have previously published photometry.

Table 1 of Massey et al. (2006) shows that the seeing conditions under which the LGGS fields were obtained ranged from 0.8 to 1.2$''$ in all filters; for most fields the prevailing seeing was around 1.0$''$. In their Table 3, these authors compared the differences in their calibrated photometry between overlapping fields using well-exposed, isolated stars and found that the median difference was several millimagnitudes. Our photometry has been calibrated relative to that of Massey et al. (2006). We compared the photometric measurements of those clusters that were located in the regions of overlap between different frames and found differences of only a few $\times0.01$ mag. While these differences are a little larger than those reported by Massey et al. (2006), this is not unexpected, since star clusters often have more extended and more complicated profiles than stars. For clusters with more than one photometric measurement in overlapping fields, we adopted the magnitude associated with the smallest statistical uncertainty.

Table 1 lists our new broad-band $UBVRI$ magnitudes and the corresponding photometric errors. The latter combine the errors associated with MAG_BEST with those related to the flux calibration, as

$$
\sigma_i^2 = \sigma_{\text{best},i}^2 + \sigma_{\text{calib},i}^2,
$$

where $i$ represents any of the $UBVRI$ bands, whereas $\sigma_{\text{best}}$ and $\sigma_{\text{calib}}$ correspond to the photometric uncertainties associated with the MAG_BEST magnitudes and flux calibration, respectively.

Since SExtractor applies apertures of different sizes to obtain MAG_BEST magnitudes, depending on the size of the object of interest, we applied aperture growth-curve corrections to all photometric measurements. In fact, although the MAG_BEST values represent the optimum magnitudes in the MAG_ISO COR approach works well for stars but poorly for elliptical (galaxy) profiles with broader wings. SExtractor also delivers automatic aperture photometry measurements of galaxies based on the first-moment algorithm of Kron (1980), MAG_AUTO. The MAG_BEST magnitudes can be automatically mapped onto MAG_AUTO if neighbors do not bias the photometry by more than 10%. In all other cases, MAG_BEST is set to equal MAG_ISO COR, because the latter measurements are not significantly affected by nearby sources. Thus, we adopted the MAG_BEST magnitudes as our final instrumental magnitudes. As a consequence, we do not need to choose the size of the aperture used. The instrumental magnitudes were calibrated in the standard Johnson–Kron–Cousins $UBVRI$ system by comparing the published magnitudes of stars from Massey et al. (2006), who calibrated their photometry using Landolt (1992) standard stars, 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. The calibration errors range from $\sim0.01$ to $\sim0.03$ mag in the $UBVRI$ bands, with more than 300 secondary standard stars available in each field. Finally, we obtained photometry for 708 objects, with 387, 563, 616, 580, and 478 sources in the individual $UBVRI$ bands, respectively, of which 276, 405, 430, 457, and 363 star clusters and candidates do not have previously published photometry.

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Since SExtractor applies apertures of different sizes to obtain MAG_BEST magnitudes, depending on the size of the object of interest, we applied aperture growth-curve corrections to all photometric measurements. In fact, although the MAG_BEST values represent the optimum magnitudes in the presence of neighboring sources, they may still systematically underestimate the total flux of extended sources by about 10% (McIntosh et al. 2005; Caldwell et al. 2008). Therefore, we corrected for this “lost” flux using the appropriate aperture corrections. We used an approximate aperture radius $r = (a^2 + b^2)^{1/2}$ for our photometry by combining half the major axis, $a$, and half the minor axis, $b$. We then calculated the aperture corrections on the basis of template growth curves (derived from the LGGS data) that were most representative of our extended star clusters. The aperture corrections are slightly different for different filters and different images: on average, they are $\sim0.36$ mag for $r \leq 3$ pixel, $\sim0.10$ mag for $3 < r \leq 5$ pixel, $\sim0.05$ mag for $5 < r \leq 7$ pixel, and $\sim0.02$ mag for $r > 7$ pixel. The maximum aperture used for our photometry is 7.19 pixel ($1'35$). We therefore used $r = 7$ pixel $\approx 1'38$ as the radius for our full sample’s aperture corrections.

Many previous studies (e.g., San Roman et al. 2009, 2010; Park & Lee 2007) used a fixed aperture of $r = 2'2$ for the photometry of all clusters and a smaller aperture, $r \approx 1'5$, for color measurements. For comparison, based on the sizes and (elliptical) profiles of the clusters in our sample, we used apertures of

| Our ID | SR ID | SM ID | $U$ (mag) | $B$ (mag) | $V$ (mag) | $R$ (mag) | $I$ (mag) |
|-------|-------|-------|-----------|-----------|-----------|-----------|-----------|
| 1     | 163   |       | 19.353 ± 0.033 | 18.127 ± 0.020 | …         | …         | …         |
| 2     | 197   |       | 19.898 ± 0.035 | 18.751 ± 0.021 | …         | …         | …         |
| 3     | 203   |       | 19.951 ± 0.034 | 20.596 ± 0.028 | 19.954 ± 0.027 | …         | …         |
| 4     | 204   |       | 19.448 ± 0.033 | 19.523 ± 0.021 | 18.856 ± 0.020 | …         | …         |
| 5     | 284   |       | 19.945 ± 0.034 | 18.686 ± 0.020 | 17.539 ± 0.018 | …         | …         |
| 6     | 316   |       | 19.890 ± 0.034 | 18.702 ± 0.020 | 17.367 ± 0.018 | …         | …         |
| 7     | 346   |       | 20.331 ± 0.038 | 20.078 ± 0.025 | 19.400 ± 0.023 | …         | …         |
| 8     | 394   |       | 17.709 ± 0.032 | 17.406 ± 0.019 | 16.998 ± 0.018 | …         | …         |
| 9     | 405   |       | 20.673 ± 0.044 | 20.493 ± 0.034 | …         | …         | …         |
| 10    | 425   |       | 21.152 ± 0.050 | 20.518 ± 0.031 | 19.286 ± 0.021 | 18.401 ± 0.019 | 17.606 ± 0.029 |

Note. "SR" and "SM" refer to the IDs of San Roman et al. (2010) and SM10, respectively.

(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 2. Comparisons of our photometric measurements with those of Park & Lee (2007) for all star clusters in common. The error bars represent a combination (addition in quadrature) of the uncertainties associated with our photometry and those from the literature.

$r \lesssim 1.5''$ for the photometry of 95% of our sample clusters. Nevertheless, the apertures adopted in both this article and previous studies result in essentially the same photometry and colors. The object names we use follow the naming convention of San Roman et al. (2010) and SM10.

Previously, Park & Lee (2007) determined integrated $BVI$ aperture photometry for 104 M33 star clusters using (mainly) CFHT images, as well as supplementary HST/WFPC2 archival images. Charge-transfer (in)efficiency (CTE) corrections were applied to the $HST$ magnitudes, and all photometry has been converted to the standard Johnson–Cousins system. Figure 2 compares our photometry with that of Park & Lee (2007), which shows that there is little systematic difference: $\Delta V = 0.006 \pm 0.001$ mag (in the sense, this paper minus Park & Lee 2007), with $\sigma = 0.349$ mag. Both our $(B - V)$ and $(V - I)$ colors show good agreement with Park & Lee (2007) down to the faintest magnitudes. The differences between both sets of photometry are $\Delta(B - V) = 0.049 \pm 0.004$ mag with $\sigma = 0.189$ mag, and $\Delta(V - I) = 0.025 \pm 0.003$ mag, $\sigma = 0.302$ mag.

Figure 3 shows the difference between our photometry and that of San Roman et al. (2009), whose database includes integrated photometry of 161 star clusters in M33 based on $HST$/ACS–WFC observations. The photometric uncertainties associated with the mean offsets are defined as $\sigma/\sqrt{N}$, where $\sigma$ is the standard deviation and $N$ is the number of data points. CTE corrections were applied and the photometry has been converted to the standard Johnson–Cousins system. Figure 3 shows comparisons of the respective sets of magnitudes and colors. Since San Roman et al. (2009) do not provide their photometric uncertainties, the error bars in Figure 3 reflect our photometric uncertainties only. Our $V$-band magnitudes are in good agreement with those of San Roman et al. (2009) down to the faintest magnitudes: $\Delta V = 0.162 \pm 0.016$ mag (this paper minus San Roman et al. 2009), with $\sigma = 0.304$ mag. However, a few objects have magnitudes that are $>0.5$ mag fainter in our database than in the tables of San Roman et al. (2009), i.e., objects 105, 110, and 148 of San Roman et al. (2009), which are marked with open circles in Figure 3. We checked the $V$-band images and found that all of these objects are located close to a few fainter neighboring sources, which are treated as independent objects in our photometry but they were regarded as stars belonging to the same cluster by San Roman et al. (2009). Both our $(B - V)$ and $(V - I)$ colors show good agreement with San Roman et al. (2009). The differences between our measurements and their photometry are $\Delta(B - V) = 0.106 \pm 0.025$ mag with $\sigma = 0.233$ mag and $\Delta(V - I) = -0.065 \pm 0.008$ mag, $\sigma = 0.361$ mag.

We also compared our photometry with the measurements of SM10, who assembled their photometry from the recent literature. Figure 4 shows the relevant comparisons. Since SM10 do not provide their photometric uncertainties, the error bars only reflect the uncertainties associated with our photometry. Our photometry is generally consistent with that of SM10: $\Delta V = 0.082 \pm 0.005$ mag (in the sense of this paper minus SM10) with $\sigma = 0.322$ mag. Again, both the $(B - V)$ and $(V - I)$ colors show good agreement with SM10 down to the faintest magnitudes. The differences between our colors and their photometry are $\Delta(B - V) = 0.069 \pm 0.006$ mag with $\sigma = 0.267$ mag and $\Delta(V - I) = 0.012 \pm 0.001$ mag, $\sigma = 0.343$ mag.

In Figure 5 we also compare our newly obtained photometric magnitudes and colors with those published by Ma (2012). The error bars shown in this figure are a combination (added in quadrature) of the uncertainties associated with our measurements and those from the literature. For all sources, the $V$-band offset is $\Delta V = -0.100 \pm 0.007$ mag (again, in the sense this paper minus Ma 2012), with $\sigma = 0.257$ mag. Our $V$-band magnitudes are in good agreement with the equivalent values of Ma (2012) for bright sources, $V < 18$ mag, while the photometry of Ma (2012) seems to be somewhat fainter than our photometry for $V > 18$ mag. In fact, Ma (2012) noted that his $V$-band photometry is systematically fainter than the previously published photometric measurements of Sarajedini & Mancone (2007), Park & Lee (2007), and San Roman et al. (2009), so this result is in line with our expectations. Our $(U - V), (B - V), (V - R),$ and $(V - I)$ colors show good agreement with the measurements of Ma (2012). The differences between our and his colors are $\Delta(U - V) = -0.151 \pm 0.013$, $\sigma = 0.244$ mag; $\Delta(B - V) = -0.068 \pm 0.005$, $\sigma = 0.154$ mag; $\Delta(V - R) = 0.049 \pm 0.004$, $\sigma = 0.157$ mag; and $\Delta(V - I) = 0.080 \pm 0.010$, $\sigma = 0.274$ mag.

Figure 6 shows the luminosity function of the M33 star clusters and candidates in our sample, which can be used to estimate the completeness of our photometry. The magnitudes are
extinction-corrected absolute $V$-band magnitudes. We adopted a distance modulus to M33 of $(m - M)_0 = 24.64$ mag (Galleti et al. 2004). Extinction determinations for these star clusters were taken from Park & Lee (2007) and San Roman et al. (2009). For star clusters without published reddening values, we adopted an average reddening of $E(V - I) = 0.06$ mag (Sarajedini et al. 2000; San Roman et al. 2009), since for a significant number of clusters deriving individual reddening values is not possible. In fact, Sarajedini et al. (2000) found that the standard deviation associated with the average reddening value is $\Delta E(V - I) = 0.02$ mag, which shows that the scatter in reddening among most M33 star clusters is not significant. Reddening variations may introduce a maximum additional uncertainty of $\sim 0.08$ mag in the $U$ band, and much smaller uncertainties in the other, redder filters, particularly in the near-infrared (NIR) bands. This is similar to the uncertainties in our photometry. We thus conclude that variations in the average reddening are unlikely to affect our fit results more significantly for clusters without prior reddening estimates than the individual reddening values determined previously for most of our other sample clusters in M33.

Using a bin size of 0.5 mag, we determined an overall limiting magnitude of $M^0_V = -4.54$ mag, which corresponds to the half-peak height of the distribution; this follows the method adopted in our previous analysis (Fan et al. 2010) of M31 globular clusters (GCs). In addition, we found that the peak of the distribution occurs at $M^0_V = -6.04 \pm 0.04$ mag, with $\sigma_{M^0_V} = 1.277$ mag, which we adopt as the completeness magnitude threshold. Note that a Gaussian “fit” does not seem to actually fit the data very well. It underpredicts cluster numbers at the bright end and somewhat overpredicts them at the faint end. Therefore, we give more weight to the bright end in our fitting routine. The faint end may not be Gaussian in (true) shape but simply be depleted because of sample incompleteness.

To further explore the completeness level of the M33 star cluster sample, we show its spatial distribution in Figure 7. The sample clusters characterized by absolute, extinction-corrected $V$-band magnitudes, $M^0_V \leq -6.04$ mag, which is the peak
Figure 5. Comparison of our photometry and colors with the equivalent measurements of Ma (2012). The error bars are a combination (added in quadrature) of the uncertainties associated with our measurements and those of Ma (2012).

Figure 6. Reddening-corrected absolute V-band magnitude ($M^0_V$) distribution of our M33 star cluster sample. The vertical line at $M^0_V = -4.54$ reflects our estimate of the sample’s 50% completeness limit.

magnitude of the distribution in Figure 6, are shown as green points, while the purple points represent the $M^0_V > -6.04$ mag star clusters in our sample. There is no evidence of any spatial differences between both samples. We fit Gaussian profiles to the distributions in the right ascension (R.A.) and declination (decl.) directions and determined the distribution’s center coordinates: R.A. = 23:449, with $\sigma = 0.153$, and decl. = 30:642, with $\sigma = 0.205$, for the bright sources; R.A. = 23:459 ($\sigma = 0.138$) and decl. = 30:623 ($\sigma = 0.192$) for the faint objects. The two center positions are shown as the plus signs in Figure 7.

3. SED FITS AND RESULTS

We constrain the ages, metallicities, and masses of the star clusters based on SED fitting using $\chi^2$ minimization. We mainly used our photometry (Table 1) from the LGGS images to do so, supplemented with the SDSS $ugriz$ photometry from San Roman et al. (2010). After elimination of those clusters for which photometry is available in too few passbands, our sample is reduced to 671 star clusters and cluster candidates. We will use this subsample for SED fitting and analysis in the following sections.

3.1. Age Estimates

As is common in relation to most ground-based observations, we can only access the integrated spectra and photometry of most extragalactic star clusters. Therefore, the ages, metallicities, and other physical parameters are obtained through analysis of the integrated data. As a matter of fact, a strong age–metallicity degeneracy would likely affect our analysis if only optical photometry were available (Worthey 1994; Arimoto 1996; Kaviraj et al. 2007). Anders et al. (2004) recommend to use NIR photometry if available. Inclusion of at least one NIR passband can significantly improve the accuracy of the resulting cluster parameters and partially break this degeneracy. In addition, de Grijs et al. (2005) and Wu et al. (2005) showed that NIR colors can greatly contribute to breaking the age–metallicity and age–extinction degeneracies. Therefore, we will combine our $UBVRi$ photometry with $JHK$ photometry from 2MASS.

7 We only apply SED fitting to clusters with photometric measurements in $\geq 3$ passbands; measurements in fewer filters lead to highly unreliable results (cf. Anders et al. 2004).
when available to disentangle the degeneracies and obtain more accurate results.

We fit the SEDs with the evolutionary tracks derived from the updated PARSEC isochrones, assuming a Chabrier (2003) lognormal stellar initial mass function (IMF). These PARSEC isochrones are available for metallicities 0.0001 \( \leq Z \leq 0.06 \) (\(-2.2 \leq [\text{M/H}] \leq +0.5 \text{ dex}\)) and for stellar masses in the range 0.1 \( \leq M/M_\odot \leq 12 \), with revised diffusion and overshooting for low-mass stars and improvements in the interpolation scheme. Note that, at present, the PARSEC isochrones do not include the thermally pulsing asymptotic giant branch (TP-AGB) phase. We adopted 24 metallicities from \( Z = 0.0001 \) to 0.06, essentially equally spaced in log \( Z \) space. The maximum age for a reliable interpolation in metallicity is 13.5 Gyr, or log(\( t/\text{yr}^{-1} \)) = 10.13. Therefore, we adopted 71 equally spaced time steps from log(\( t/\text{yr}^{-1} \)) = 6.6 (4 Myr) to log(\( t/\text{yr}^{-1} \)) = 10.1 (12.6 Gyr) in steps of \( \Delta \text{log}(t/\text{yr}^{-1}) = 0.05 \). The models return isochrone tables and integrated SSP magnitudes for a number of photometric systems. We adopted the SDSS ugriz, Johnson–Cousins UBVRI, and 2MASS JHK systems.

The magnitudes were corrected for reddening (obtained previously; see above) assuming a Cardelli et al. (1989) extinction curve. Since the wavelengths ranges covered by the SDSS ugriz and Johnson–Cousins UBVRI systems are essentially the same, it is not necessary to use both for our SED fitting. We assigned priority to using the broad-band Johnson–Cousins UBVRI photometry, since these filters have wider bandwidths and, hence, the photometry could potentially have higher signal-to-noise ratios, all else being equal. Where broad-band Johnson–Cousins magnitudes were not available, the SDSS ugriz photometry was used. Thus, the cluster ages \( t \) could be determined by comparing, in the \( \chi^2 \) sense, the PARSEC SSP synthesis models with the observed SEDs and adopting \( Z \) as a free parameter, i.e.,

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

where \( m_{\lambda_i}^{\text{mod}}(t, Z) \) is the integrated magnitude in the \( i \)th filter of a theoretical SSP at age \( t \) and for metallicity \( Z \), \( m_{\lambda_i}^{\text{obs}} \) represents the observed, integrated magnitude in the same filter, \( m_{\lambda_i} = UBVRI, ugriz, JHK \) when 2MASS data is available or \( m_{\lambda_i} = UBVRI, ugriz \) when 2MASS data is not available (all magnitudes were transformed to the AB magnitude system for our SED fits). The errors, which are used as weights \( (\pm 1/\sigma^2) \) by the fitting routine, are calculated as

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

Here, \( \sigma_{\text{obs},i} \) is the observational uncertainty; \( \sigma_{\text{mod},i} \) represents the uncertainty associated with the model itself, for the \( i \)th filter. Following de Grijs et al. (2005), Wu et al. (2005), Fan et al. (2006, 2010), Ma et al. (2007, 2009), and Wang et al. (2010), we adopt \( \sigma_{\text{mod},i} = 0.05 \) mag.

The estimated ages with 1\( \sigma \) errors of the M33 star clusters are listed in Table 2. We estimated the uncertainty associated with a given parameter by fixing all other parameters to their best values, then varied the parameter of interest, and recorded an error corresponding to the 1\( \sigma \) \( \chi^2 \) value.

Our newly estimated ages, compared with previous results from the literature, are plotted in Figure 8. The top panels are comparisons of SM10 and our results, and the middle panels are those for our estimates and the results of San Roman

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8 http://stev.oapd.inaf.it/cgi-bin/cmd
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Figure 8. Comparisons of our age, metallicity, and mass estimates with those of (top) SM10 and (middle) San Roman et al. (2009). We also compare the parameter estimates of SM10 and San Roman et al. (2009) in the bottom row.

Table 2
Ages, Metallicities, and Masses of the M33 Star Clusters

| Object | Age (Gyr) | (Fe/H) (dex) | log(M_Cl) (M_⊙) |
|--------|----------|-------------|------------------|
| SR1001 | 2.510 ± 0.775 | −2.301 ± 0.150 | 4.184 ± 0.144 |
| SR1009 | 1.580 ± 0.260 | 0.477 ± 0.088 | 5.154 ± 0.175 |
| SR1012 | 1.120 ± 0.259 | −1.602 ± 0.122 | 4.148 ± 0.129 |
| SR1013 | 0.006 ± 0.002 | 0.301 ± 1.049 | 2.688 ± 0.112 |
| SR1020 | 1.580 ± 0.185 | −0.824 ± 0.150 | 4.025 ± 0.100 |
| SR1021 | 0.022 ± 0.008 | −1.602 ± 0.122 | 3.032 ± 0.081 |
| SR1022 | 3.160 ± 1.810 | −2.301 ± 0.238 | 4.683 ± 0.244 |
| SR1024 | 3.980 ± 1.400 | −2.301 ± 0.150 | 4.565 ± 0.004 |
| SR1028 | 2.000 ± 0.465 | −0.699 ± 0.301 | 3.914 ± 0.059 |
| SR1029 | 1.000 ± 0.233 | −1.456 ± 0.412 | 3.666 ± 0.093 |

(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 latter authors compare MSTO photometry in the observed CMD with Girardi et al. (2000) theoretical isochrones assuming a metal abundance $Z = 0.004$, which is the mean of the disk abundance gradient in M33 (cf. Kim et al. 2002; Sarajedini et al. 2006; San Roman et al. 2009). In the top panels, we note that SM10’s cluster ages and masses exhibit a general one-to-one trend with respect to our results, although the scatter is relatively large. In fact, all cluster ages and masses in SM10 were taken from the Ma et al. (2001, 2002a, 2002b, 2004a, 2004b) series of articles. These latter authors derived these parameters based on SED fits based on GISSEL 96 (G. Bruzual & S. Charlot, unpublished). This is a similar approach to our method, but based on different theoretical models and photometry. In this article, we use some of the most up-to-date SSP synthesis models currently available, while our photometry is based on (more recent) observations with the Kitt Peak 4 m Telescope. In addition, we used NIR photometry here, which can be used successfully to partially break the well-known age–metallicity degeneracy affecting broad-band SED analyses. A comparison of the results of San Roman et al. (2009) and the newly derived parameters presented here reveals that the systematic differences, in a logarithmic sense, in the ages, masses, and metallicities between our estimates and those of SM10 (i.e., Ma et al.) are $−0.23 ± 0.77$ dex, $−0.32 ± 0.73$ dex, and 0.08 ± 1.49 dex, respectively. This scatter is partially caused by the different metallicities adopted and partially because of stochastic sampling effects (see, e.g.,...
Anders et al. (2013). However, the ages from San Roman et al. (2009) are systematically younger for clusters we determine as $>1$ Gyr old, while they are systematically older than our estimates for objects we return as $<0.1$ Gyr old. This may be partially caused by the different analysis methods or by application of different SSP models with different IMFs.

To check if our method introduces any biases, we also compare the fit results for San Roman et al. (2009) and those of SM10. This comparison shows the same trends as seen in the comparisons of San Roman et al. (2009) and our results, which indicates that the CMD fitting method of San Roman et al. (2009) may be affected by a systematic bias (see the bottom panels of Figure 8). Since San Roman et al. (2009) adopted a single metal abundance for their CMD fits, we do not show a comparison of their metallicities with those of SM10. In fact, as San Roman et al. (2009) point out, the isochrone-derived ages for clusters younger than $\sim1$ Gyr exhibit very little sensitivity to the assumed metal abundance. This implies that any metallicity difference between our results and those of San Roman et al. (2009) will likely have insignificant effects on the final cluster parameters derived since almost all clusters in the sample of San Roman et al. (2009) are younger than 1 Gyr. Even if San Roman et al. (2009) had allowed their metal abundances to vary, their fit results would unlikely be affected significantly. Note that this is rather different in comparison with SED fits. In addition, we adopted the extinction values of San Roman et al. (2009).

Park et al. (2009) compared cluster ages derived from resolved CMDs with those from integrated photometry and found that ages derived from resolved CMDs cover a relatively smaller range—$7.0 \lesssim \log(t \, yr^{-1}) \lesssim 8.5$—than those estimated based on integrated colors and SEDs (e.g., Chandar et al. 1999, 2002; Ma et al. 2001, 2002a, 2002b, 2002c, 2004a, 2004b). In addition, Santos & Frogel (1997) found that stochastic sampling effects can strongly affect the integrated $VJHK$ magnitudes of star clusters with ages $7.5 < \log(t \, yr^{-1}) < 9.25$, in particular for less massive clusters (Buzzoni 1989; Barmby & Jalilian 2012; Silva-Villa & Larsen 2011).

In fact, Silva-Villa & Larsen (2011) discussed the effects of stochastic sampling on CMD fits; such effects are particularly prominent for low-mass star clusters. Since star clusters are composed of finite numbers of stars, stochastic sampling of the stellar IMF can significantly affect the derived integrated cluster parameters, such as their ages, metallicities, and masses. Recently, Anders et al. (2013) quantified the effects of stochastic sampling of stellar IMFs based on a set of GALEV SSP models for a wide range of (input) masses, metallicities, foreground extinction values, and photometric uncertainties for their model star clusters. They derive the accuracy of the integrated parameter determination in different age ranges based on performing fully sampled integrated-SED fits. For low-mass ($\sim10^3 M_\odot$) clusters that are older than 10 Myr, the dispersion in $\log(t \, yr^{-1})$ could be as much as $\sim1$–2 dex, while the dispersion in $\log(M_\odot/M_\odot)$ could be of the same order for $[Fe/H] = 0.0$ dex, foreground $E(B-V) = 0.0$ mag, and assuming photometric uncertainties of 0.1 mag for all $UBVRIJHK$ magnitudes. In addition, using a variety of metallicities and different combinations of photometric passbands, stochastic sampling effects can even lead to differences of $\Delta \log(t \, yr^{-1}) > 1$ dex. The offset between the estimates of SM10 and San Roman et al. (2009) can thus be understood easily. This type of effect could also partially explain the offsets in the derived parameters between SM10 and our determinations, as well as those between SM10 and San Roman et al. (2009).

We emphasize that San Roman et al. (2009) also point out that, since their photometry is generally not deep enough to detect the MSTO, few of their clusters are returned as older than 1 Gyr. The middle panel in the central row of Figure 8 shows a comparison of the mass estimates of San Roman et al. (2009) with our new determinations. We note that the masses derived by San Roman et al. (2009) range from $5 \times 10^3 M_\odot$ to $5 \times 10^4 M_\odot$, while our estimates cover the range from $\sim10^2 M_\odot$ to $\sim10^4 M_\odot$. This difference can largely be traced back to the differences in our derived ages.

The left-hand panels in the top and second rows of Figure 9 show the age distribution of our sample clusters in M33, as well as the distribution of a representative sample of M31 star clusters (Fan & de Grijs 2012), for a bin size of 0.3 dex. To allow a reasonable comparison, the parameters, such as age, metallicity, and mass of the M31 star clusters were also all derived based on the PARSEC models, using the photometric data from Fan & de Grijs (2012). We also plot the age distribution of the Milky Way star cluster sample, which is composed of both GCs and open clusters (OCs). In addition, the age estimates of LMC star clusters taken from Baumgardt et al. (2013) are also plotted in this diagram, for comparison. We note that the M33 star clusters in our sample exhibit two peaks, at ages of $\sim10$ Myr and $\sim1$ Gyr. The mean ages of the cluster samples are $\langle t \rangle = 8.68, 9.17, 8.46$, and $8.48$ for M33, M31, MW, and the LMC, respectively. For M33, the clusters with ages in excess of 10 Gyr were most likely created during the epoch when the galaxy formed, while the young star clusters might have been created in a number of mergers during the last few Gyr or by the postulated recent galactic encounter with M31 a few Gyr ago, suggested by McConnachie et al. (2009). The age distribution of the star clusters in M31 is dominated by clusters with ages between 1 Gyr and the WMAP9 age of 13.77 $\pm$ 0.06 Gyr (Bennett et al. 2013). The age distribution of the Milky Way star clusters is based on the combination of that of the OCs collected in Dias et al. (2002)—the New Catalog of Optically Visible Open Clusters and Candidates; version 3.3—and the GCs, for which we assumed the WMAP9 age. The mean age of the Milky Way’s OCs is similar to that of the M33 and LMC clusters. This latter similarity implies that both galaxies have recently gone through one or more periods of active star (cluster) formation. It is clear that there is a much higher fraction of young star clusters in M33 (30.6% are older than 2 Gyr) than in M31, where 55.8% of the clusters are older than 2 Gyr.

The middle panels of Figure 9, from the top to the third row, show the metallicity distributions of star clusters in M33, M31, and the Milky Way for a bin size of $\Delta[Fe/H] = 0.25$ dex. The mean values of the three distributions are $[Fe/H] = -1.01, -0.43$, and $-0.19$ dex. The metallicity distribution of the M33 star clusters comes from our SSP fits based on the PARSEC models, while the metallicity distribution of the M31 star clusters is from the data of Fan & de Grijs (2012), also based on the PARSEC models. The metallicity distribution of the Milky Way GCs has been plotted based on the GC catalog of Harris (2010) and that of the OCs is based on the (Dias et al. 2002) catalog, which was most recently updated in 2013 and includes 201 Milky Way OCs with metallicity measurements. We computed the weighted metallicity of the two cluster samples using the numbers of GCs and OCs as weights, which is therefore dominated by the metallicity distribution of the OCs.

### 3.2. Masses of the M33 Star Clusters

We calculated the clusters’ theoretical mass-to-light ratios ($M/L_V$) using the PARSEC models, luminosities based on conversion of the $V$-band fluxes, and a distance modulus of...
Figure 9. Estimated age, mass, and metallicity distributions of the star clusters and candidates in M33, M31, and the Milky Way based on the PARSEC models. The vertical dashed lines represent the mean values of the distributions. The photometric data of the M33 clusters comes from this paper, while the SEDs of the M31 globular-like clusters were analyzed by Fan & de Grijs (2012). The Milky Way star clusters are composed of GCs and OCs, for which the distributions are based on Harris (2010), the updated catalog of Dias et al. (2002), and Gnedin & Ostriker (1997). The distributions of the LMC star clusters are based on Baumgardt et al. (2013).

\[(m - M)_0 = 24.64\] mag. The resulting masses are listed in Table 2. Figure 9 (right column) shows the mass distribution of the M33 star clusters in our sample, as well as the masses of the M31 and Milky Way clusters. The masses of the Galactic GCs were calculated by Gnedin & Ostriker (1997), while those of 650 OCs with mass estimates are from Piskunov et al. (2008). As before, these Galactic cluster mass estimates were combined, using as weights the total numbers of clusters of different types. For comparison, we also include the LMC star cluster data from Baumgardt et al. (2013). The bin size is \[\Delta \log (M_{\odot}) = 0.3\] dex. The mean mass of the M33 clusters is \[\log (M_{\odot}) = 4.25 (1.78 \times 10^5 M_{\odot})\] while the mean values for the M31 star clusters, the combined sample of Galactic star clusters, and the LMC clusters are \[\log (M_{\odot}) = 5.43 (2.69 \times 10^5 M_{\odot}), \log (M_{\odot}) = 4.18 (1.51 \times 10^4 M_{\odot}), \log (M_{\odot}) = 3.27 (5.24 \times 10^2 M_{\odot}), \text{ and } \log (M_{\odot}) = 4.64 (5.24 \times 10^2 M_{\odot})\], respectively. Figure 9 shows that the mean mass of the star clusters in M33, which is similar to that of the LMC clusters, is much lower than the equivalent masses in M31 and the Milky Way, suggesting that the M33 cluster population on the whole is dominated by lower-mass clusters.

The mass–metallicity relation (MMR) for star clusters in the “blue sequence” (which is known as the “blue tilt”) has been discussed for many external galaxies, e.g., for a sample of six giant elliptical galaxies (Harris 2009a), M87 (Peng et al. 2009; Harris 2009b), the Sombrero galaxy (Harris et al. 2010), and M31 (Fan et al. 2009). Self-enrichment was considered a reasonable explanation by both Bailin & Harris (2009) and...
Fan & de Grijs (2014), who suggested that the level of star formation is controlled by supernova feedback, and the efficiency scaling is proportional to the proto-cloud mass. Since we have derived the masses and metallicities of the M33 clusters, we can investigate their MMR. In Figure 10, we plot cluster masses as a function of metallicity for our sample star clusters. The filled triangles with associated error bars represent the mean values and $\sigma$'s for each bin. The bin size is 0.5 dex in metallicity. For low metallicities, $[\text{Fe}/\text{H}] < -0.8$ dex, the cluster masses seem to decrease with metallicity, while for $[\text{Fe}/\text{H}] \geq -0.8$ dex, the cluster masses increase with increasing metallicity.

Figure 11 shows the extinction-corrected absolute magnitudes as a function of age for our sample star clusters. The solid lines represent theoretical isochrones from the updated PARSEC models for masses of $10^3$, $10^4$, $10^5$, and $10^6 \, M_\odot$, for a metallicity of $Z = 0.004$. The masses of most star clusters and candidates are between $10^3 \, M_\odot$ and $10^5 \, M_\odot$. The less massive clusters, $M_\text{cl} < 10^5 \, M_\odot$, tend to be young (<2 Gyr) while clusters with $M_\text{cl} > 10^5 \, M_\odot$ are generally old (>2 Gyr).

The age–metallicity relations of extragalactic star clusters have been studied by many authors (e.g., de Grijs & Anders 2006; Wang et al. 2010; Fan et al. 2010). Figure 12 shows the age-versus-mass estimates of our M33 sample clusters, as well as the so-called “fading line,” which is roughly equivalent to the $\sim 50\%$ completeness limit. The theoretical line is based on the PARSEC SSP models for a metallicity of $Z = 0.004$. For the detection limit, an absolute magnitude of $M_V \approx -5$ mag is estimated from Figure 6. Indeed, most star clusters lie above the line. The small number of clusters found below the fading line may be due to either a possibly variable photometric completeness level or underestimated extinction. A few faint, young (<20 Myr old) clusters could be young OCs. Note that there are three overdensity regions in this figure, at (1) $\log(t \, \text{yr}^{-1}) \approx 7.3$ (20 Myr), (2) $\log(t \, \text{yr}^{-1}) \approx 9$ (1 Gyr), and (3) the WMAP9 age (~13.7 Gyr); the latter represents the subset of the cluster population that seems to have formed during the time of the galaxy’s formation.

4. SUMMARY

We have obtained UBVRI photometry for 708 star clusters and cluster candidates in M33, which were selected from San Roman et al. (2010), including 387, 563, 616, 580, and 478 objects in the UBVRI bands, respectively, of which 276, 405, 430, 457, and 363 did not have previously published UBVRI photometry. The SExtractor code was applied to derive the photometry from LGGS archival images, which cover 0.8 deg$^2$ along the major axis of M33.

We compared our photometry with previous measurements, which showed that our photometry is generally consistent with
previous measurements in all filters. The ages, metallicities, and masses of our sample clusters were derived by comparison of their observed SEDs with parsec SSP synthesis models. The fits show that only 205 of the 671 clusters (30.55%) are older than 2 Gyr, which is a much smaller fraction than that derived for the M31 globular-like clusters (55.80%), suggesting that the M33 cluster population is dominated by young star clusters (<1 Gyr). We also note that the mean mass of the M33 star clusters is $1.78 \times 10^5 M_\odot$, which is much less massive than that of the M31 sample ($2.69 \times 10^5 M_\odot$) and similar to that of LMC cluster population ($1.51 \times 10^4 M_\odot$), but higher than that of Milky Way star clusters (including both GCs and OCs: $5.24 \times 10^2 M_\odot$). This may be related to the fact that the mass of M33 is lower than that of M31, and the gravitational potential is not large enough to produce as many GCs as in M31. Instead, the star-formation history of M33 may be similar to that of the LMC. As for the Milky Way, the recent few Gyr have seen the galaxy undergo quiescent evolution (a low star-formation rate).

On the other hand, the mean metallicity of the M33 clusters ([Fe/H] = −1.01 dex) is much lower than that of the M31 star clusters ([Fe/H] = −0.43 dex) and also of the Milky Way star clusters ([Fe/H] = −0.19 dex), suggesting that its star-formation history has been rather different from those of either M31 or the Milky Way. Based on the cluster mass distributions we also found that the mean mass of star clusters in M33 is similar to that in the LMC but much lower than that in M31 and higher than that in the Milky Way, indicating that M31 underwent more violent star formation than either M33 or the LMC. We also note that stochastic sampling effects can significantly affect our SED fit results for low-mass clusters (i.e., $M_{cl} \lesssim 10^3 M_\odot$), potentially leading to large differences in integrated cluster ages, metallicities, and masses (Anders et al. 2013). The effects of stochasticity in the clusters’ stellar mass functions become weaker with increasing cluster mass. However, even for the highest-mass clusters, $M_{cl} \simeq 2 \times 10^5 M_\odot$, the uncertainties in the derived logarithmic ages are 0.05–0.25 dex; the equivalent uncertainties pertaining to the derived masses are 0.09–0.17 dex. Although these uncertainties are sometimes significant, obtaining accurate, high-resolution spectroscopic observations for statistically large samples of extragalactic star clusters is often prohibitive, particularly if observing time on significantly oversubscribed (large) telescopes is sought. Broadband imaging and parameter determination based on sophisticated SED fits is the realistic yet a poor man’s alternative approach.

The broad-band SED uncertainties can be further reduced for specific age ranges, e.g., for young clusters that exhibit H\alpha emission, which places additional constraints on the most likely age range. At present, a number of teams are working on quantifying the effects of stochastic sampling; although the underlying message is that such effects may have significant implications in terms of the precision of the derived physical parameters, we argue that a proper understanding of one’s uncertainties is of the utmost importance. One should keep these issues in mind when dealing with physical cluster parameters based on broad-band observations.

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