

## SPECTRAL ENERGY DISTRIBUTIONS, AGES, AND METALLICITIES OF STAR CLUSTERS IN M33

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Received 2001 May 14; accepted 2001 June 26

### ABSTRACT

In this paper, we present CCD spectrophotometry of the star clusters that were detected by Chandar, Bianchi, & Ford in the nearby spiral galaxy M33. The images were obtained with the Beijing Astronomical Observatory 60/90 cm Schmidt Telescope in 13 intermediate-band filters from 3800 to 10000 Å. The observations cover the whole area of M33 with a total integration of 32.75 hr from 1995 September 23 to 2000 August 28. This provides a multicolor map of M33 in pixels of  $1''.7 \times 1''.7$ . By aperture photometry, we obtain the spectral energy distributions of these star clusters. Using theoretical stellar population synthesis models, we also obtain the distributions of age and metallicity of these star clusters. These clusters formed continuously from  $\sim 3 \times 10^6$ – $10^{10}$  yr and have a large span of metallicity from  $Z = 0.0004$  to 0.05.

*Key words:* galaxies: evolution — galaxies: individual (M33) — galaxies: star clusters

*On-line material:* color figure

### 1. INTRODUCTION

The importance of the study of star clusters is difficult to overstate, especially in Local Group galaxies. Star clusters, which represent, in distinct and luminous “packets,” single-age and single-abundance points and encapsulate at least a partial history of the parent galaxy’s evolution, can provide a unique laboratory for studying the ongoing and past star formation in the parent galaxy. Determination of elemental abundances in cluster stars is crucial to our understanding of the chemical evolution and star formation histories of the galaxy. In addition, studies of star cluster populations could help our understanding of the relationships between cluster formation and the physical morphology of the parent galaxy.

M33 is a small Scd Local Group galaxy, about 15 times farther from us than the LMC (distance modulus is 24.64; Freedman, Wilson, & Madore 1991; Chandar, Bianchi, & Ford 1999a). It is interesting and important because it represents a morphological type intermediate between the largest “early-type” spirals and the dwarf irregulars in the Local Group (Chandar et al. 1999a). Our collaboration, the Beijing-Arizona-Taiwan-Connecticut (BATC) Multicolor Sky Survey (Fan et al. 1996; Zheng et al. 1999) already had this spiral galaxy as part of its galaxy calibration program. The BATC program uses the 60/90 cm Schmidt Telescope at the Xinglong Station of the Beijing Astronomical Observatory, with its focal plane equipped with a  $2048 \times 2048$  Ford CCD, and has custom designed a set of 15 intermediate-band filters to do spectrophotometry for preselected  $1 \text{ deg}^2$  regions of the northern sky with this CCD system.

For M33, a database of star clusters has been yielded from ground-based work (Hiltner 1960; Kron & Mayall 1960; Christian & Schommer 1982, 1988; Melnick & D’Odorico 1978) and from the *Hubble Space Telescope* (*HST*) images (Chandar et al. 1999a). Chandar et al. (1999a) presented the first unbiased, representative sample of star

clusters, sampling a variety of environments from outer regions to spiral arms and central regions, and can be used to probe the global properties of M33.

Since the pioneering work of Tinsley (1972) and Searle, Sargent, & Bagnuolo (1973), evolutionary population synthesis has become a standard technique to study the stellar populations of galaxies. This is a result of the improvement in the theory of the chemical evolution of galaxies, star formation, stellar evolution and atmospheres, and of the development of synthesis algorithms and the availability of various evolutionary synthesis models. A comprehensive compilation of such models was presented by Leitherer et al. (1996) and Kennicutt (1998). More widely used models are those from the Padova and Geneva group (see, e.g., Schaerer & de Koter 1997; Schaerer & Vacca 1998; Bressan, Chiosi, & Tantalo 1996; Chiosi et al. 1998), GISSEL96(Charlot & Bruzual 1991; Bruzual & Charlot 1993; G. Bruzual & S. Charlot 1996, unpublished), PEGASE (Fioc & Rocca-Volmerange 1997), and STARBURST99 (Leitherer et al. 1999).

In this paper, we present the spectral energy distributions (SEDs) of the star clusters that were detected by Chandar et al. (1999a) in M33 and study the distributions of age and metallicity of these clusters by using the theoretical evolutionary population synthesis methods. The multicolor photometry is powerful to provide the accurate SEDs for these stellar clusters.

The outline of the paper is as follows: Details of observations and data reduction are given in § 2. In § 3, we provide a brief description of the stellar population synthesis models of G. Bruzual & S. Charlot (1996, unpublished). The distributions of metallicity and age are given in § 4. The summary and discussion are presented in § 5.

### 2. SAMPLE OF STAR CLUSTERS, OBSERVATIONS, AND DATA REDUCTION

#### 2.1. Sample of Star Clusters

The sample of star clusters in this paper is from Chandar et al. (1999a), who used 20 multiband *HST* WFPC2 fields to search for star clusters much closer to the nucleus of M33 than previous studies. Since these star clusters populate the variety of environments from the outer regions to spiral

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arms and central regions, they can be used to probe the global properties of the parent galaxy. At the same time, the accurate positions are presented in Table 2 of Chandar et al. (1999a). So, as a first step, we select these star clusters to be studied and obtain their SEDs by aperture photometry. The distribution of age and metallicity for these star clusters are derived by using the theoretical evolutionary population synthesis methods. Clusters 17, 39, 41, and 42 are not included in our sample because of their low signal-to-noise ratio in the images of some BATC filters.

### 2.2. CCD Image Observation

The large field multicolor observations of the spiral galaxy M33 were obtained in the BATC photometric system. The telescope used is the 60/90 cm  $f/3$  Schmidt Telescope of the Beijing Astronomical Observatory (BAO), located at the Xinglong station. A Ford Aerospace  $2048 \times 2048$  CCD camera with  $15 \mu\text{m}$  pixel size is mounted at the Schmidt focus of the telescope. The field of view of the CCD is  $58' \times 58'$ , with a pixel scale of  $1''.7$ .

The multicolor BATC filter system includes 15 intermediate-band filters, covering the total optical wavelength range from 3000 to 10000 Å (see Fan et al. 1996). The filters

were specifically designed to avoid contamination from the brightest and most variable night-sky emission lines. A full description of the BAO Schmidt Telescope, CCD, data-taking system, and definition of the BATC filter systems are detailed elsewhere (Fan et al. 1996; Zheng et al. 1999). The images of M33 covering its whole optical body were accumulated in 13 intermediate band filters with a total exposure time of about 32.75 hr from 1995 September 23 to 2000 August 28. The CCD images are centered at R.A. =  $01^{\text{h}}33^{\text{m}}50^{\text{s}}.58$  and decl. =  $30^{\circ}39'08''.4$  (J2000). The dome flat-field images were taken by using a diffuse plate in front of the correcting plate of the Schmidt Telescope. For flux calibration, the Oke-Gunn primary flux standard stars HD 19445, HD 84937, BD +26°2606, and BD +17°4708 were observed during photometric nights. The parameters of the filters and the statistics of the observations are given in Table 1. Figure 1 is a “true-color” estimate of M33 generated by using the BATC03 (4210 Å) filter image for blue, BATC07 (5785 Å) for green, and BATC10 (7010 Å) for red.

### 2.3. Image Data Reduction

The data were reduced with standard procedures, including bias subtraction and flat fielding of the CCD images,



FIG. 1.—True-color estimate of M33 generated by using the BATC03 (4210 Å) filter image for blue, BATC07 (5785 Å) for green, and BATC10 (7010 Å) for red; the image is balanced by making the background old population orange and the hot stars blue. The center (origin) of the image is located at R.A. =  $01^{\text{h}}33^{\text{m}}50^{\text{s}}.58$ , decl. =  $30^{\circ}39'08''.4$  (J2000.0). North is up, and east is to the left. [See the electronic edition of the *Journal* for a color version of this figure.]

TABLE 1  
PARAMETERS OF THE BATC FILTERS AND STATISTICS OF  
OBSERVATIONS

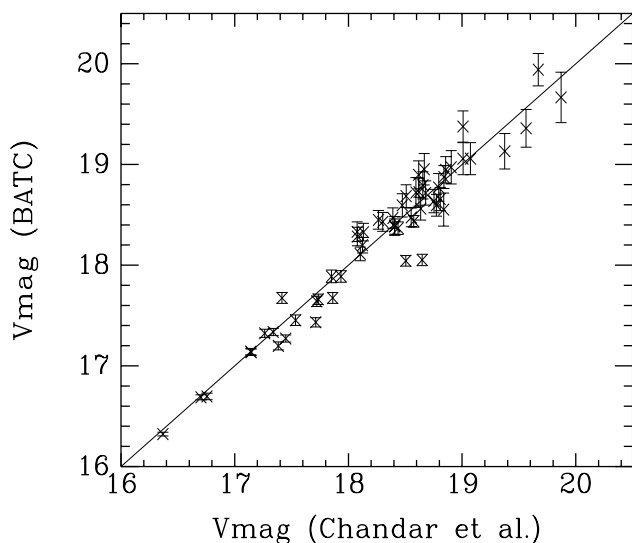
No. (1)	Name (2)	$\text{cw}^a$ ( $\text{\AA}$ ) (3)	Exp. (hr) (4)	N.img <sup>b</sup> (5)	rms <sup>c</sup> (6)
1.....	BATC03	4210	00:55	04	0.024
2.....	BATC04	4546	01:05	04	0.023
3.....	BATC05	4872	03:55	19	0.017
4.....	BATC06	5250	03:19	15	0.006
5.....	BATC07	5785	04:38	17	0.011
6.....	BATC08	6075	01:26	08	0.016
7.....	BATC09	6710	01:09	08	0.006
8.....	BATC10	7010	01:41	08	0.005
9.....	BATC11	7530	02:07	10	0.017
10.....	BATC12	8000	03:00	11	0.003
11.....	BATC13	8510	03:15	11	0.005
12.....	BATC14	9170	01:15	05	0.011
13.....	BATC15	9720	05:00	26	0.009

<sup>a</sup> Central wavelength for each BATC filter.

<sup>b</sup> Image numbers for each BATC filter.

<sup>c</sup> Zero-point error, in magnitudes, for each filter as obtained from the standard stars.

with an automatic data reduction software named PIPELINE 1, developed for the BATC multicolor sky survey (Fan et al. 1996; Zheng et al. 1999). The flat-fielded images of each color were combined by integer pixel shifting. The cosmic rays and bad pixels were corrected by comparison of multiple images during combination. The images were recentered and position-calibrated using the *HST* Guide Star Catalog. The absolute flux of intermediate-band filter images was calibrated using observations of standard stars. Fluxes, as observed through the BATC filters for the Oke-Gunn stars, were derived by convolving the SEDs of these stars with the measured BATC filter transmission functions (Fan et al. 1996). Column (6) in Table 1 gives the zero-point error, in magnitudes, for the standard stars in each filter. The formal errors we obtain for these stars in the 13 BATC filters are  $\leq 0.02$  mag. This indicates that we can define the standard BATC system to an accuracy of  $\leq 0.02$  mag.



## 2.4. Integrated Photometry

For each star cluster, aperture photometry was used to obtain magnitudes. For avoiding contamination from nearby objects, a smaller aperture of  $6''.8$ , which corresponds to a diameter of 4 pixels in Ford CCDs, was adopted. Considering the large seeing of the Xinglong station, aperture corrections were computed using isolated stars. Since these star clusters sample a variety of environments from outer regions to spiral arms and central regions, background subtraction is difficult. We determined the background in annulus of from 2 to 5 pixels from each star cluster. In this annulus, we fitted each row of the image by linear median fitting to obtain a surface. Then we repeat this process in the column direction of the surface that is obtained in the row of fitting. After this fit, we reject points higher and lower than 30% of the mean background. Lastly, we obtained the final smoothed surface of background. Using this surface of background, we made the background subtraction for each cluster. The SEDs for the 56 star clusters were obtained. Table 2 contains the following information: Column (1) is the cluster number, which is taken from Chandar et al. (1999a). Columns (2)–(14) show the magnitudes of different bands. The second line of each star cluster is the uncertainty of magnitude of the corresponding band. The uncertainties for each filter take into account the error from the object count rate, sky variance, and instrument gain.

## 2.5. Comparison with Previous Photometry

Using the Landolt standards, Zhou et al. (2001) presented the relationships between the BATC intermediate-band system and *UBVRI* broadband system by the catalogs of Landolt (1983, 1992) and Galadí-Enríquez, Trullols, & Jordi (2000). We show the coefficients of the fits in equations (1) and (2).

$$m_B = m_{04} + (0.2218 \pm 0.033)(m_{03} - m_{05}) + 0.0741 \pm 0.033, \quad (1)$$

$$m_V = m_{07} + (0.3233 \pm 0.019)(m_{06} - m_{08}) + 0.0590 \pm 0.010. \quad (2)$$

Using equations (1) and (2), we transformed the magnitudes of the star clusters in BATC03, BATC04, and BATC05

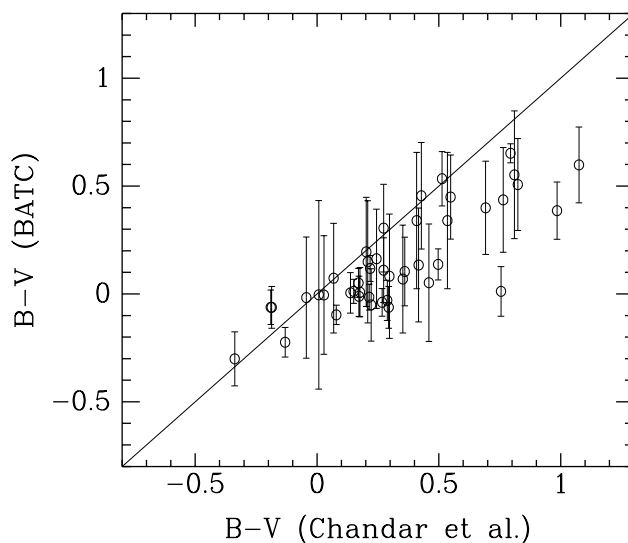


FIG. 2.—Comparison of cluster photometry with previous measurements

TABLE 2  
SEDs OF 56 STAR CLUSTERS

No. (1)	03 (2)	04 (3)	05 (4)	06 (5)	07 (6)	08 (7)	09 (8)	10 (9)	11 (10)	12 (11)	13 (12)	14 (13)	15 (14)
1 .....	18.617 0.073	18.650 0.078	18.017 0.039	18.819 0.100	18.647 0.081	18.769 0.107	17.066 0.024	18.620 0.098	18.520 0.095	18.282 0.098	18.835 0.245	17.801 0.060	18.528 0.185
2 .....	16.684 0.019	16.623 0.019	16.760 0.019	16.653 0.021	16.635 0.018	16.648 0.022	16.492 0.019	16.392 0.018	16.189 0.017	16.125 0.017	15.954 0.020	15.702 0.012	15.736 0.017
3 .....	17.611 0.030	17.552 0.029	17.672 0.028	17.589 0.031	17.660 0.032	17.727 0.039	17.753 0.038	17.836 0.044	17.841 0.046	17.868 0.064	17.976 0.108	17.923 0.062	17.956 0.105
4 .....	17.879 0.037	17.816 0.036	17.853 0.032	17.815 0.038	17.824 0.037	17.799 0.042	17.782 0.039	17.723 0.040	17.864 0.048	17.898 0.067	18.029 0.118	17.795 0.056	17.970 0.110
5 .....	18.864 0.085	18.685 0.079	18.687 0.077	18.415 0.082	18.706 0.085	18.537 0.086	18.517 0.089	18.612 0.091	18.518 0.101	18.800 0.114	19.165 0.161	18.925 0.155	18.677 0.168
6 .....	17.611 0.030	17.552 0.029	17.672 0.028	17.589 0.031	17.660 0.032	17.727 0.039	17.753 0.038	17.836 0.044	17.841 0.046	17.868 0.064	17.976 0.108	17.923 0.062	17.956 0.105
7 .....	16.990 0.019	16.874 0.018	16.660 0.013	17.116 0.022	17.211 0.023	17.338 0.029	16.375 0.014	17.337 0.030	17.570 0.038	17.668 0.054	17.697 0.085	17.187 0.033	18.227 0.136
8 .....	19.042 0.083	18.912 0.083	18.910 0.083	18.915 0.083	18.896 0.078	18.941 0.081	18.179 0.075	18.664 0.076	18.759 0.079	18.852 0.083	18.688 0.094	18.646 0.088	19.728 0.129
9 .....	20.062 0.106	20.574 0.108	20.157 0.098	20.084 0.094	19.921 0.098	20.203 0.104	20.005 0.099	20.255 0.114	19.745 0.115	19.620 0.130	20.314 0.182	19.683 0.160	19.736 0.161
10 .....	18.649 0.066	18.452 0.056	18.515 0.051	18.578 0.066	18.522 0.062	18.536 0.074	18.618 0.073	18.536 0.074	18.603 0.082	18.552 0.114	18.400 0.156	18.516 0.100	18.179 0.126
11 .....	19.561 0.153	19.051 0.098	18.994 0.080	18.823 0.085	18.500 0.063	18.520 0.075	18.186 0.052	18.114 0.053	17.985 0.050	17.948 0.067	17.673 0.081	17.618 0.046	17.539 0.071
12 .....	19.485 0.092	19.382 0.091	19.468 0.092	19.233 0.091	19.302 0.096	19.182 0.094	19.115 0.101	19.037 0.100	18.911 0.105	18.796 0.098	18.902 0.111	18.617 0.107	18.305 0.109
13 .....	19.226 0.106	18.983 0.087	19.020 0.077	19.092 0.101	18.906 0.084	19.128 0.121	19.545 0.165	19.113 0.120	19.407 0.165	18.900 0.146	19.446 0.380	18.868 0.131	19.324 0.335
14 .....	17.411 0.024	17.287 0.022	17.291 0.019	17.287 0.023	17.252 0.021	17.209 0.023	17.275 0.024	17.181 0.023	17.089 0.023	17.179 0.032	17.087 0.045	17.134 0.029	17.088 0.044
15 .....	19.634 0.150	19.213 0.105	19.133 0.084	19.111 0.102	18.995 0.089	19.099 0.115	19.196 0.119	19.203 0.128	18.917 0.104	18.928 0.145	18.902 0.222	18.788 0.118	19.156 0.276
16 .....	17.302 0.022	17.133 0.019	17.190 0.017	17.234 0.022	17.218 0.021	17.254 0.025	17.211 0.022	17.186 0.023	17.209 0.025	17.206 0.034	17.242 0.055	17.237 0.032	17.204 0.052
18 .....	19.821 0.161	19.538 0.126	19.594 0.113	19.689 0.151	19.602 0.143	19.673 0.180	19.655 0.161	19.631 0.172	19.403 0.147	19.543 0.246	19.703 0.455	19.433 0.202	18.885 0.210
19 .....	18.973 0.088	18.775 0.074	18.757 0.063	18.681 0.072	18.570 0.065	18.655 0.083	18.523 0.068	18.496 0.072	18.497 0.076	18.320 0.093	18.297 0.143	18.237 0.079	18.089 0.116
20 .....	19.110 0.102	18.755 0.077	18.704 0.063	18.453 0.063	18.307 0.054	18.254 0.061	18.050 0.048	17.831 0.043	17.698 0.040	17.706 0.055	17.522 0.072	17.392 0.038	17.303 0.058
21 .....	17.265 0.023	17.317 0.024	17.354 0.021	17.469 0.029	17.426 0.025	17.630 0.035	17.702 0.036	18.012 0.050	17.929 0.049	17.869 0.060	18.319 0.139	18.026 0.065	18.402 0.149
22 .....	18.655 0.065	18.231 0.046	18.126 0.037	18.008 0.040	17.760 0.032	17.794 0.038	17.739 0.035	17.634 0.034	17.601 0.035	17.492 0.043	17.561 0.071	17.490 0.040	17.322 0.056
23 .....	18.988 0.085	18.756 0.071	18.676 0.057	18.581 0.065	18.335 0.051	18.407 0.064	18.389 0.059	18.355 0.062	18.282 0.062	18.206 0.079	18.341 0.139	18.107 0.067	18.239 0.125
24 .....	18.886 0.081	18.877 0.082	18.871 0.071	18.996 0.097	18.950 0.093	19.111 0.127	19.204 0.129	19.400 0.166	19.688 0.228	19.831 0.372	20.399 0.990	20.540 0.654	20.083 0.731
25 .....	19.193 0.079	19.220 0.068	19.285 0.073	18.817 0.061	18.833 0.071	18.871 0.074	18.880 0.079	19.007 0.072	18.573 0.070	18.792 0.092	18.779 0.188	19.118 0.145	18.834 0.173
26 .....	17.465 0.029	17.372 0.028	17.481 0.027	17.517 0.035	17.407 0.028	17.557 0.038	17.567 0.038	17.558 0.040	17.514 0.041	17.426 0.045	17.391 0.063	17.389 0.041	17.411 0.065
27 .....	18.789 0.088	18.497 0.071	18.494 0.061	18.400 0.072	18.209 0.055	18.202 0.064	18.145 0.059	18.109 0.062	17.984 0.059	17.902 0.065	17.762 0.083	17.543 0.045	17.443 0.063
28 .....	17.258 0.024	16.754 0.017	16.600 0.013	16.458 0.014	16.163 0.010	16.149 0.012	15.967 0.010	15.914 0.010	15.866 0.010	15.777 0.011	15.722 0.015	15.689 0.010	15.660 0.014
29 .....	18.982 0.056	18.598 0.049	18.614 0.043	18.313 0.041	18.267 0.036	18.184 0.038	18.170 0.039	18.163 0.043	18.229 0.052	18.134 0.051	18.173 0.055	18.077 0.062	18.218 0.088
30 .....	18.703 0.070	18.186 0.046	18.486 0.052	18.273 0.053	18.108 0.043	18.176 0.053	18.888 0.101	18.329 0.062	18.378 0.069	18.404 0.093	18.616 0.173	18.651 0.108	18.769 0.197
31 .....	19.396 0.129	18.951 0.089	18.873 0.071	18.770 0.081	18.528 0.064	18.464 0.071	18.438 0.065	18.375 0.067	18.271 0.065	18.212 0.083	18.033 0.109	18.474 0.097	18.192 0.125
32 .....	16.614 0.015	16.507 0.014	16.573 0.012	16.644 0.016	16.643 0.015	16.689 0.017	16.666 0.016	16.651 0.017	16.601 0.017	16.538 0.021	16.542 0.031	16.488 0.018	16.424 0.028
33 .....	17.396 0.024	17.141 0.020	17.196 0.018	17.037 0.019	17.043 0.018	16.915 0.019	16.920 0.018	16.828 0.018	16.877 0.020	16.986 0.027	16.808 0.035	16.912 0.024	16.969 0.040

TABLE 2—Continued

No.	03	04	05	06	07	08	09	10	11	12	13	14	15
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
34.....	17.663	17.560	17.613	17.587	17.601	17.647	17.660	17.715	17.859	17.867	17.772	17.894	17.754
	0.032	0.029	0.026	0.031	0.030	0.036	0.034	0.038	0.046	0.063	0.089	0.059	0.087
35.....	17.204	17.045	17.076	17.138	17.090	17.181	17.172	17.211	17.285	17.253	17.300	17.208	17.313
	0.019	0.017	0.015	0.019	0.018	0.022	0.020	0.023	0.025	0.034	0.055	0.030	0.055
36.....	18.771	18.303	18.563	18.257	18.468	18.420	18.363	18.111	18.163	18.921	19.179	18.687	18.599
	0.071	0.048	0.051	0.048	0.057	0.064	0.056	0.048	0.054	0.154	0.308	0.112	0.179
37.....	18.779	18.613	19.215	18.490	18.518	18.541	18.821	18.276	18.167	18.190	18.124	18.023	17.643
	0.079	0.069	0.110	0.065	0.067	0.079	0.112	0.063	0.061	0.087	0.128	0.070	0.081
38.....	19.003	18.854	18.737	18.722	18.742	18.748	18.641	18.767	18.783	18.636	18.545	18.725	18.201
	0.093	0.083	0.064	0.079	0.079	0.094	0.080	0.096	0.104	0.126	0.181	0.126	0.131
40.....	17.711	17.656	17.540	17.919	18.069	18.182	17.369	18.177	18.494	18.309	18.707	18.382	18.474
	0.024	0.023	0.019	0.028	0.031	0.038	0.020	0.039	0.046	0.068	0.120	0.063	0.117
43.....	18.437	18.357	18.236	18.387	18.424	18.531	17.687	18.481	18.450	18.346	18.555	17.908	18.032
	0.044	0.041	0.034	0.034	0.035	0.034	0.018	0.038	0.032	0.035	0.052	0.032	0.037
44.....	17.629	17.556	17.624	17.642	17.607	17.658	17.679	17.669	17.727	17.688	17.634	17.576	17.486
	0.030	0.029	0.026	0.032	0.030	0.037	0.035	0.038	0.042	0.054	0.079	0.045	0.069
45.....	19.634	19.213	19.133	19.111	18.995	19.099	19.196	19.203	18.917	18.928	18.902	18.788	19.156
	0.150	0.105	0.084	0.102	0.089	0.115	0.119	0.128	0.104	0.145	0.222	0.118	0.276
46.....	19.400	18.828	18.827	18.727	18.499	18.617	18.559	18.487	18.643	18.419	18.505	18.379	18.839
	0.133	0.082	0.071	0.080	0.063	0.082	0.074	0.074	0.090	0.101	0.169	0.090	0.227
47.....	17.547	17.357	17.414	17.382	17.214	17.227	17.183	17.165	17.209	17.296	17.288	17.159	17.220
	0.025	0.023	0.021	0.025	0.023	0.027	0.023	0.025	0.027	0.039	0.059	0.032	0.059
48.....	18.878	18.853	18.967	18.862	18.691	18.790	19.521	18.639	18.805	18.790	18.593	18.692	18.948
	0.088	0.089	0.084	0.095	0.075	0.096	0.185	0.087	0.108	0.136	0.172	0.118	0.238
49.....	19.374	18.537	18.556	18.518	18.081	18.068	17.862	17.905	17.928	17.743	17.797	17.810	17.752
	0.151	0.073	0.065	0.078	0.049	0.057	0.046	0.050	0.054	0.059	0.094	0.059	0.090
50.....	18.633	18.272	18.249	18.411	18.227	18.282	18.205	18.457	18.367	18.246	18.172	18.094	18.173
	0.065	0.049	0.041	0.059	0.048	0.059	0.052	0.071	0.069	0.083	0.120	0.067	0.119
51.....	18.626	18.513	18.554	18.519	18.446	18.375	18.508	18.317	18.475	18.506	18.553	19.044	18.452
	0.080	0.073	0.077	0.093	0.102	0.098	0.092	0.100	0.082	0.109	0.176	0.081	0.107
52.....	19.742	19.233	19.102	19.202	18.741	18.901	18.707	18.744	18.805	18.592	18.570	18.688	18.253
	0.161	0.104	0.080	0.109	0.072	0.098	0.077	0.086	0.096	0.111	0.170	0.111	0.126
53.....	20.342	19.691	19.543	19.240	19.240	19.054	18.938	18.800	18.634	18.488	18.661	18.481	18.162
	0.285	0.157	0.118	0.108	0.115	0.114	0.092	0.088	0.080	0.108	0.204	0.097	0.126
54.....	19.080	18.806	18.628	18.401	18.217	18.071	17.889	17.803	17.820	17.716	17.730	17.586	17.648
	0.088	0.069	0.051	0.050	0.045	0.046	0.036	0.036	0.038	0.052	0.084	0.042	0.076
55.....	18.598	18.248	18.212	18.174	18.005	18.024	18.027	17.939	17.940	17.884	17.797	17.659	17.742
	0.060	0.045	0.038	0.045	0.038	0.045	0.043	0.042	0.045	0.059	0.084	0.044	0.079
56.....	18.662	18.454	18.469	18.414	18.308	18.342	18.362	18.343	18.471	18.437	18.508	18.196	18.627
	0.068	0.058	0.051	0.060	0.054	0.065	0.061	0.065	0.078	0.105	0.175	0.078	0.193
57.....	19.939	19.766	19.506	19.471	18.933	19.041	18.786	18.848	18.532	18.321	18.256	18.157	18.248
	0.206	0.177	0.120	0.144	0.091	0.118	0.086	0.099	0.080	0.095	0.142	0.075	0.139
58.....	18.762	18.537	18.585	18.546	18.387	18.478	18.388	18.534	18.572	18.430	18.127	18.359	18.628
	0.074	0.061	0.055	0.065	0.057	0.072	0.061	0.076	0.083	0.105	0.126	0.090	0.197
59.....	18.467	18.294	18.284	18.194	17.923	17.976	17.872	17.689	17.484	17.382	17.338	17.155	17.045
	0.046	0.038	0.034	0.037	0.033	0.036	0.031	0.029	0.026	0.034	0.050	0.028	0.041
60.....	18.798	18.714	18.664	18.648	18.676	18.703	18.689	18.783	18.806	18.713	19.077	18.649	18.950
	0.074	0.070	0.057	0.068	0.071	0.085	0.077	0.091	0.099	0.131	0.291	0.113	0.255

bands to ones in the  $B$  band, and those in the BATC06, BATC07, and BATC08 bands to ones in the  $V$  band. For clusters 1, 7, 37, 40, and 43, we change  $m_{05}$  to  $m_{04}$  because of the strong emission or absorption lines in BATC05 band. Figure 2 plots the comparison of  $V$  (BATC) and  $B-V$  (BATC) photometry with previously published measurements (Chandar et al. 1999a). Table 3 also shows this comparison. The mean  $V$  magnitude and color differences (this paper's values minus the values of Chandar et al. 1999a) are  $\langle \Delta V \rangle = -0.009 \pm 0.025$  and  $\langle \Delta(B-V) \rangle = -0.179 \pm 0.039$ , respectively. The uncertainties in  $B$  (BATC) and  $V$  (BATC) have been added linearly, i.e.,  $\sigma_B = \sigma_{04} + 0.2218(\sigma_{03} + \sigma_{05})$ , and  $\sigma_B = \sigma_{07} + 0.3233(\sigma_{06} + \sigma_{08})$ , to

reflect the error in the three filter measurements. For the colors, we also added the errors linearly, i.e.,  $\sigma_{(B-V)} = \sigma_B + \sigma_V$ .

### 3. DATABASES OF SIMPLE STELLAR POPULATIONS

A simple stellar population (SSP) is defined as a single generation of coeval stars with fixed parameters, such as metallicity, initial mass function, etc. (Buzzoni 1999). SSPs are the basic building blocks of the synthetic spectra of galaxies that can be used to infer the formation and subsequent evolution of the parent galaxies (Jablonka et al. 1996). They are modeled by a collection of stellar evolutionary tracks with different masses and initial chemical com-

TABLE 3  
COMPARISON OF CLUSTER PHOTOMETRY WITH PREVIOUS MEASUREMENTS

No. (1)	$V$ (Chandar et al.) (2)	$V$ (BATC) (3)	$B-V$ (Chandar et al.) (4)	$B-V$ (BATC) (5)
1.....	$18.594 \pm 0.018$	$18.722 \pm 0.148$	$0.028 \pm 0.020$	$-0.005 \pm 0.275$
2.....	$16.756 \pm 0.006$	$16.696 \pm 0.032$	$0.214 \pm 0.006$	$-0.015 \pm 0.060$
3.....	$17.416 \pm 0.010$	$17.674 \pm 0.054$	$0.294 \pm 0.023$	$-0.062 \pm 0.097$
4.....	$17.851 \pm 0.006$	$17.888 \pm 0.063$	$0.176 \pm 0.011$	$0.008 \pm 0.114$
5.....	$18.621 \pm 0.013$	$18.726 \pm 0.139$	$0.068 \pm 0.019$	$0.073 \pm 0.254$
6.....	$17.862 \pm 0.008$	$17.674 \pm 0.054$	$-0.186 \pm 0.013$	$-0.062 \pm 0.097$
7.....	$17.384 \pm 0.006$	$17.198 \pm 0.039$	$-0.131 \pm 0.006$	$-0.224 \pm 0.069$
8.....	$18.856 \pm 0.019$	$18.947 \pm 0.131$	$0.352 \pm 0.030$	$0.069 \pm 0.250$
9.....	$19.670 \pm 0.032$	$19.942 \pm 0.161$	...	$0.686 \pm 0.314$
10.....	$18.774 \pm 0.016$	$18.595 \pm 0.108$	...	$-0.039 \pm 0.190$
11.....	$18.808 \pm 0.016$	$18.657 \pm 0.115$	...	$0.594 \pm 0.265$
12.....	$19.008 \pm 0.021$	$19.377 \pm 0.155$	$0.297 \pm 0.034$	$0.082 \pm 0.288$
13.....	$18.667 \pm 0.019$	$18.953 \pm 0.156$	$0.208 \pm 0.016$	$0.149 \pm 0.283$
14.....	$17.339 \pm 0.005$	$17.336 \pm 0.036$	$0.170 \pm 0.008$	$0.051 \pm 0.067$
15.....	$19.008 \pm 0.023$	$19.058 \pm 0.159$	$0.409 \pm 0.028$	$0.340 \pm 0.316$
16.....	$17.449 \pm 0.005$	$17.271 \pm 0.036$	$0.267 \pm 0.009$	$-0.039 \pm 0.064$
18.....	$19.870 \pm 0.046$	$19.666 \pm 0.250$	$0.007 \pm 0.038$	$-0.004 \pm 0.437$
19.....	$18.752 \pm 0.016$	$18.637 \pm 0.116$	...	$0.260 \pm 0.223$
20.....	$18.302 \pm 0.005$	$18.430 \pm 0.094$	...	$0.489 \pm 0.208$
21.....	$17.713 \pm 0.008$	$17.433 \pm 0.046$	$-0.190 \pm 0.008$	$-0.062 \pm 0.080$
22.....	$17.935 \pm 0.007$	$17.888 \pm 0.058$	$0.513 \pm 0.016$	$0.534 \pm 0.126$
23.....	$18.264 \pm 0.010$	$18.450 \pm 0.093$	$0.548 \pm 0.017$	$0.449 \pm 0.195$
24.....	$18.904 \pm 0.017$	$18.972 \pm 0.166$	$-0.044 \pm 0.016$	$-0.017 \pm 0.281$
25.....	$18.840 \pm 0.018$	$18.875 \pm 0.114$	$0.692 \pm 0.039$	$0.399 \pm 0.216$
26.....	$17.535 \pm 0.022$	$17.453 \pm 0.052$	$0.172 \pm 0.027$	$-0.011 \pm 0.093$
27.....	$18.077 \pm 0.022$	$18.332 \pm 0.098$	$0.273 \pm 0.035$	$0.305 \pm 0.203$
28.....	$16.368 \pm 0.015$	$16.322 \pm 0.019$	$0.794 \pm 0.014$	$0.652 \pm 0.044$
29.....	$18.437 \pm 0.035$	$18.368 \pm 0.062$	$0.985 \pm 0.059$	$0.386 \pm 0.133$
30.....	$18.124 \pm 0.041$	$18.198 \pm 0.077$	$0.273 \pm 0.037$	$0.110 \pm 0.150$
31.....	$18.508 \pm 0.031$	$18.686 \pm 0.113$	$0.428 \pm 0.040$	$0.455 \pm 0.247$
32.....	$16.703 \pm 0.016$	$16.687 \pm 0.025$	$0.079 \pm 0.013$	$-0.097 \pm 0.045$
33.....	$17.141 \pm 0.020$	$17.141 \pm 0.031$	$0.218 \pm 0.018$	$0.118 \pm 0.060$
34.....	$17.722 \pm 0.021$	$17.641 \pm 0.051$	$0.137 \pm 0.020$	$0.005 \pm 0.094$
35.....	$17.145 \pm 0.017$	$17.135 \pm 0.031$	$0.150 \pm 0.015$	$0.012 \pm 0.056$
36.....	$18.553 \pm 0.034$	$18.474 \pm 0.093$	$0.222 \pm 0.033$	$-0.051 \pm 0.168$
37.....	$18.636 \pm 0.033$	$18.561 \pm 0.113$	$0.244 \pm 0.033$	$0.163 \pm 0.230$
38.....	$18.655 \pm 0.032$	$18.793 \pm 0.135$	$0.202 \pm 0.040$	$0.195 \pm 0.253$
40.....	$18.505 \pm 0.010$	$18.043 \pm 0.052$	$-0.338 \pm 0.010$	$-0.301 \pm 0.125$
43.....	$18.575 \pm 0.018$	$18.436 \pm 0.057$	$0.755 \pm 0.039$	$0.012 \pm 0.115$
44.....	$17.735 \pm 0.007$	$17.661 \pm 0.052$	$0.288 \pm 0.009$	$-0.030 \pm 0.093$
45.....	$19.074 \pm 0.024$	$19.058 \pm 0.159$	$0.535 \pm 0.026$	$0.340 \pm 0.316$
46.....	$18.474 \pm 0.013$	$18.594 \pm 0.116$	$0.764 \pm 0.017$	$0.436 \pm 0.243$
47.....	$17.264 \pm 0.005$	$17.323 \pm 0.040$	$0.497 \pm 0.007$	$0.137 \pm 0.072$
48.....	$18.794 \pm 0.100$	$18.773 \pm 0.137$	$0.417 \pm 0.026$	$0.134 \pm 0.264$
49.....	$18.079 \pm 0.011$	$18.285 \pm 0.092$	$0.824 \pm 0.017$	$0.507 \pm 0.213$
50.....	$18.132 \pm 0.006$	$18.328 \pm 0.087$	$0.360 \pm 0.014$	$0.104 \pm 0.159$
51.....	$18.838 \pm 0.022$	$18.552 \pm 0.164$	$0.459 \pm 0.026$	$0.052 \pm 0.272$
52.....	$18.618 \pm 0.016$	$18.897 \pm 0.139$	$0.810 \pm 0.027$	$0.552 \pm 0.296$
53.....	$19.563 \pm 0.027$	$19.359 \pm 0.187$	...	$0.583 \pm 0.434$
54.....	$18.407 \pm 0.010$	$18.383 \pm 0.076$	$1.075 \pm 0.020$	$0.598 \pm 0.176$
55.....	$18.104 \pm 0.006$	$18.112 \pm 0.068$	...	$0.295 \pm 0.135$
56.....	$18.408 \pm 0.008$	$18.390 \pm 0.094$	...	$0.181 \pm 0.178$
57.....	$19.375 \pm 0.015$	$19.131 \pm 0.176$	...	$0.805 \pm 0.425$
58.....	$18.391 \pm 0.006$	$18.468 \pm 0.101$	...	$0.182 \pm 0.190$
59.....	$18.649 \pm 0.009$	$18.052 \pm 0.056$	...	$0.356 \pm 0.112$
60.....	$18.679 \pm 0.008$	$18.717 \pm 0.121$	...	$0.101 \pm 0.220$

positions, supplemented with a library of stellar spectra for stars at different evolutionary stages in evolution synthesis models. In order to study the integrated properties of star clusters in M33, as the first step, we use the SSPs of Galaxy Isochrone Synthesis Spectra Evolution Library (hereafter GSSP; G. Bruzual & S. Charlot 1996, unpublished) because they are simple and reasonably well understood.

### 3.1. Spectral Energy Distribution of GSSPs

The G. Bruzual & S. Charlot (1996, unpublished) study has extended the Bruzual & Charlot (1993) evolutionary population synthesis models. The updated version provides the evolution of the spectrophotometric properties for a wide range of stellar metallicity. They are based on the stellar evolution tracks computed by Bressan et al. (1993), Fagotto et al. (1994) and Girardi et al. (1996), who use the radiative opacities of Iglesias, Rogers, & Wilson (1992). This library includes tracks for stars with metallicities of  $Z = 0.0004, 0.004, 0.008, 0.02, 0.05,$  and  $0.1$ , with the helium abundance given by  $Y = 2.5Z + 0.23$ . (The reference solar metallicity is  $Z_{\odot} = 0.02$ .) The stellar spectra library is from Lejeune, Cuisinier, & Buser (1997, 1998) for all the metallicities listed above, which in turn consists of R. L. Kurucz (1995, private communication) spectra for the hotter stars (O–K), Bessell et al. (1991) and Fluks et al. (1994) spectra for M giants, and Allard & Hauschildt (1995) spectra for M

dwarfs. GSSP models assume an initial Salpeter (1955) mass function of  $\Phi(M) = AM^{-\alpha}$ , with  $\alpha = 2.35$  and normalization constant  $A = 1$ , a lower cutoff of  $M_l = 0.1 M_{\odot}$ , and an upper cutoff of  $M_u = 125 M_{\odot}$  (Sawicki & Yee 1998).

### 3.2. Integrated Colors of GSSPs

Kong et al. (2000) have obtained the age, metallicity, and interstellar medium reddening distribution for M81. They found the best match between the intrinsic colors and the predictions of GSSP for each cell of M81. To determine the distributions of age and metallicity of the star clusters in M33, we follow the method of Kong et al. (2000). Since the observational data are integrated luminosities, we need to convolve the SED of GSSP with BATC filter profiles to obtain the optical and near-infrared integrated luminosity for comparisons (Kong et al. 2000). The integrated luminosity,  $L_{\lambda_i}(t, Z)$ , of the  $i$ th BATC filter can be calculated with

$$L_{\lambda_i}(t, Z) = \frac{\int F_{\lambda}(t, Z)\phi_i(\lambda)d\lambda}{\int \phi_i(\lambda)d\lambda}, \quad (3)$$

where  $F_{\lambda}(t, Z)$  is the spectral energy distribution of the GSSP of metallicity  $Z$  at age  $t$ , and  $\phi_i(\lambda)$  is the response function of the  $i$ th filter of the BATC filter system ( $i = 3, 4, \dots, 15$ ), respectively.

The absolute luminosity can be obtained if we know the distance to M33 and the extinction along the line of sight.

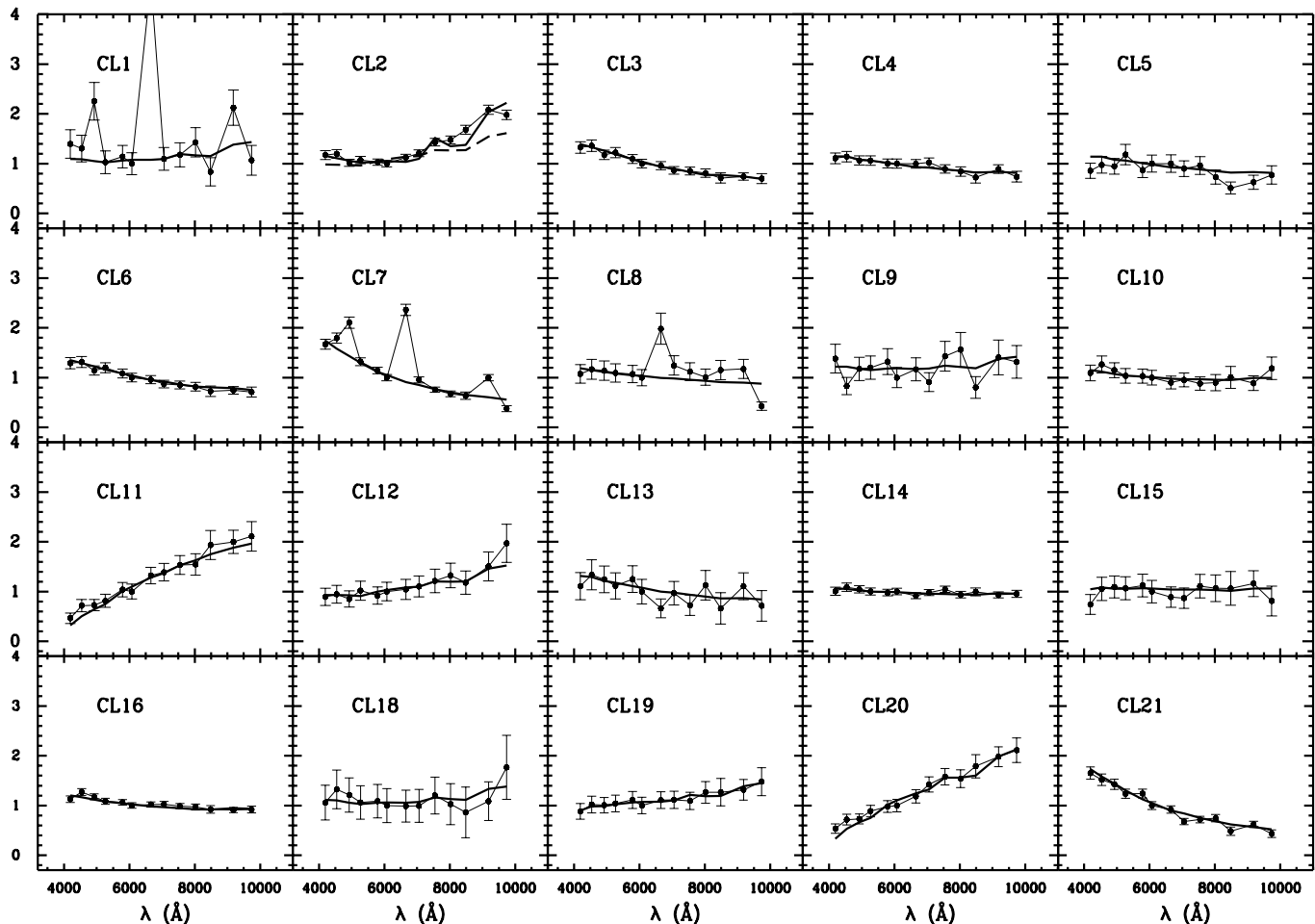
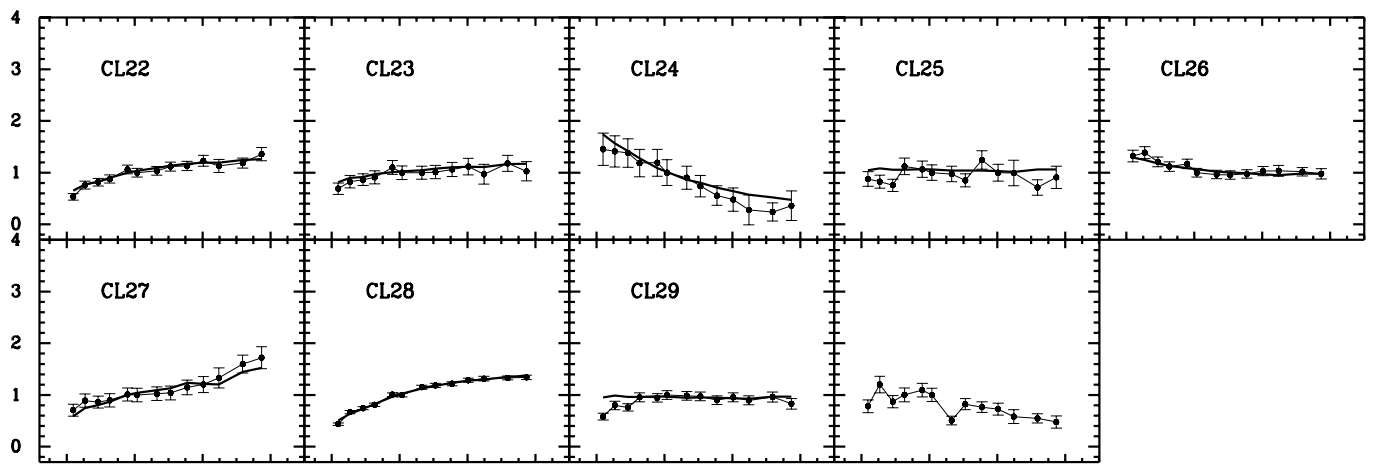
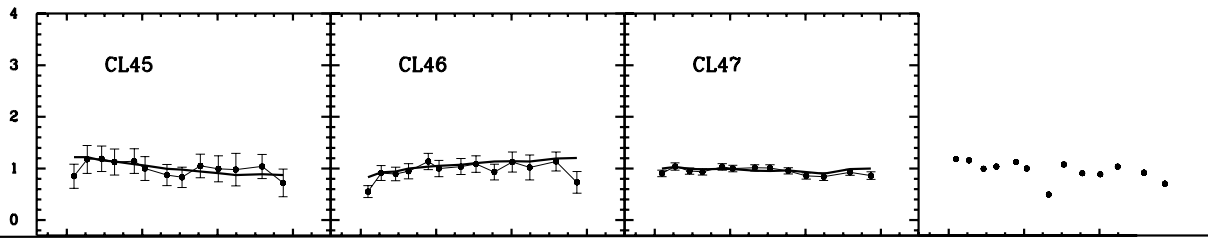


FIG. 3.—Map of the best fit of the integrated color of an SSP with intrinsic integrated color for 56 star clusters. The thick line represents the integrated color of an SSP, and the filled circle represents the intrinsic integrated color of a star cluster.







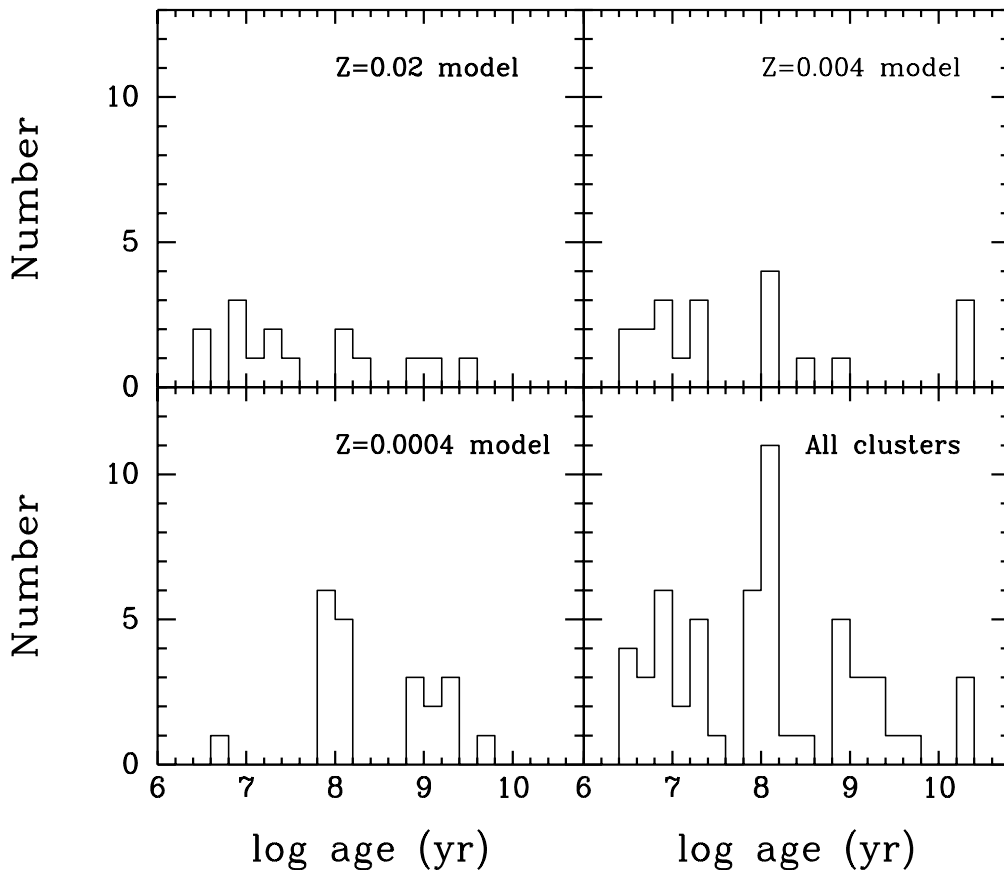


FIG. 4.—Histogram of M33 cluster ages

noise ratios are not high enough because of the strong background. (These clusters distribute mainly in the spiral arms and central regions.) As a result, the metallicities of the old clusters derived via the technique of Kong et al. (2000) are also somewhat uncertain. In our paper, there are 10 clusters, the ages of which are 1 Gyr or older than 1 Gyr. We calculated their metallicities using the method of Kong et al. (2000), except for clusters 31, 52, and 57, since the magnitude uncertainties of these three clusters are too large. Then we obtained their reddenings and ages. The results are listed in Table 5. From this table and Table 4, we can see that the metallicities of clusters 11 and 54 are not consistent by two methods. We also see that, except for clusters 20 and 59, the cluster ages derived by the two methods are consistent. The values of reddening obtained by the method of Kong et al. (2000) are not consistent with ones of Chandar et al. (1999b), except for clusters 20, 22, and 28. However, as we know, the reddening is difficult to estimate.

## 5. SUMMARY AND DISCUSSION

In this paper, we have for the first time obtained the SEDs of 56 star clusters of M33 in 13 intermediate colors with the BAO 60/90 cm Schmidt Telescope. Below, we summarize our main conclusions.

1. Using the images obtained with the Beijing Astronomical Observatory 60/90 cm Schmidt Telescope in 13 intermediate-band filters from 3800 to 10000 Å, we obtained the SEDs of the star clusters that were detected by Chandar et al. (1999a).

2. Using theoretical stellar population synthesis models, we obtained the distributions of age and metallicity of these star clusters. These clusters formed continuously from  $\sim 3 \times 10^6$ – $10^{10}$  yr and have a large span of metallicity from  $Z = 0.0004$  to 0.05.

With  $\sim 10$  Å resolution spectrophotometry ( $\lambda\lambda 3700$ – $5500$ ), Christian & Schommer (1983) presented that M33 star clusters have a range of ages ( $\sim 10^7$ – $10^{10}$  yr). Using the integrated *UBV* photometry and *IUE*  $\lambda\lambda 1200$ – $3000$  spectra, Ciani, D’Odorico, & Benvenuti (1984) studied the minuscule “bulge” population of M33 and found that a multigeneration model, where a young component (age  $\sim 10^7$  yr) and an old, metal-poor one (age  $\sim 5 \times 10^9$  yr) are superposed, gives the best fit to the observed data. Schmidt, Bica, & Alloin (1990) applied a population synthesis method that uses a star cluster spectral library and a grid of the star cluster spectral properties as a function of age and metallicity (Bica & Alloin 1986a, 1986b, 1987) to the bluish nucleus of M33 and gave an age of less than  $5 \times 10^8$  yr for the dominant blue bulge population. From the histogram of ages in this paper, we can see that some old clusters in our sample appear to be coeval with the old population of the bulge. Chandar et al. (1999b, 1999c) also estimated ages for the star clusters of this paper by comparing the *UBV* and far-UV photometric measurements (Chandar et al. 1999a, 1999c) to integrated colors from theoretical models by Bertelli et al. (1994) and found that these clusters formed continuously from  $\sim 4 \times 10^6$ – $10^{10}$  yr. Our results are consistent with the conclusions of Chandar et al. (1999b, 1999c).

TABLE 4

AGE AND METALLICITY DISTRIBUTION OF 56 STAR CLUSTERS

No.	Metallicity (Z)	Age (log yr)	No.	Metallicity (Z)	Age (log yr)
(1)	(2)	(3)	(1)	(2)	(3)
1.....	0.02000	7.260	30.....	0.00400	6.620
2.....	0.05000	6.860	31.....	0.00040	9.207
3.....	0.00400	6.620	32.....	0.02000	6.880
4.....	0.00040	8.009	33.....	0.00400	8.009
5.....	0.00040	8.009	34.....	0.00040	7.806
6.....	0.00400	6.820	35.....	0.00040	7.806
7.....	0.00400	6.439	36.....	0.00040	7.806
8.....	0.00040	6.620	37.....	0.02000	6.940
9.....	0.02000	7.477	38.....	0.02000	8.255
10.....	0.00400	7.320	40.....	0.00400	6.420
11.....	0.00400	10.301	43.....	0.02000	7.121
12.....	0.02000	6.940	44.....	0.00400	7.220
13.....	0.00040	7.806	45.....	0.00040	8.009
14.....	0.00400	6.980	46.....	0.00040	8.957
15.....	0.00400	8.009	47.....	0.02000	8.057
16.....	0.00400	7.079	48.....	0.00040	8.009
18.....	0.02000	7.279	49.....	0.00040	9.342
19.....	0.00400	6.940	50.....	0.02000	8.057
20.....	0.02000	9.544	51.....	0.00040	7.806
21.....	0.02000	6.580	52.....	0.00040	9.107
22.....	0.00040	9.255	53.....	0.00400	8.957
23.....	0.00040	8.957	54.....	0.00040	9.009
24.....	0.02000	6.520	55.....	0.00040	8.957
25.....	0.00400	8.009	56.....	0.00040	8.009
26.....	0.00400	7.241	57.....	0.00400	10.279
27.....	0.02000	8.857	58.....	0.00400	6.960
28.....	0.00040	9.796	59.....	0.02000	9.107
29.....	0.00400	8.009	60.....	0.00040	7.806

To disentangle age, metallicity, and reddening in SSPs, we adopted the  $E(B-V)$  values presented in Chandar et al. (1999b). These values may be somewhat uncertain. In order to see clearly how the uncertainties of  $E(B-V)$  affect the

TABLE 5

METALLICITY, REDDENING, AND AGE DISTRIBUTION OF SEVEN STAR CLUSTERS

No.	Metallicity (Z)	$E(B-V)$	Age (log yr)
11.....	0.00099	0.200	10.30
20.....	0.00719	0.110	10.30
22.....	0.00186	0.140	9.23
28.....	0.00023	0.050	10.30
49.....	0.00040	0.010	9.92
54.....	0.00890	0.010	9.40
59.....	0.01447	0.010	10.28

derived age and metallicity, we adopt an uncertainty of 0.03 mag of the  $E(B-V)$  values given in Chandar et al. (1999b). The results appear that an uncertainty of 0.03 mag in  $E(B-V)$  hardly affects the derived ages and metallicities on the averages but have a somewhat larger affect on the older clusters.

We would like to thank the anonymous referee for his/her insightful comments and suggestions that improved this paper. We are grateful to the Padova group for providing us with a set of theoretical isochrones and SSPs. We also thank G. Bruzual and S. Charlot for sending us their latest calculations of SSPs and for explanations of their code. The BATC Survey is supported by the Chinese Academy of Sciences, the Chinese National Natural Science Foundation and the Chinese State Committee of Sciences and Technology. The project is also supported in part by the National Science Foundation (grant INT 93-01805) and by Arizona State University, the University of Arizona, and Western Connecticut State University.

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