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# SPECTRAL ENERGY DISTRIBUTIONS AND AGE ESTIMATES OF 78 STAR CLUSTERS IN M33

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## ABSTRACT

In this third paper of our series, we present CCD spectrophotometry of 78 star clusters that were detected by Chandar, Bianchi, & Ford in the nearby spiral galaxy M33. CCD images of M33 were obtained as a part of the BATC Multicolor Sky Survey of the sky in 13 intermediate-band filters from 3800 to 10000 Å. By aperture photometry, we obtain the spectral energy distributions of these 78 star clusters. As Chandar, Bianchi, & Ford did, we estimate the ages of our sample clusters by comparing the photometry of each object with theoretical stellar population synthesis models for different values of metallicity. We find that the sample clusters formed continuously in M33 from $\sim 3 \times 10^6$ to $10^{10}$ yr. This conclusion is consistent with Chandar, Bianchi, & Ford. The results also show that there are two peaks in cluster formation at $\sim 8 \times 10^6$ and $\sim 10^9$ yr in these clusters.

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

## 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. For example, globular clusters can be used to provide a lower limit to the age of the parent galaxy, provided their ages can be ascertained, and to study the properties of the parent galaxy soon after its formation.

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). In addition, at a distance of $\sim$840 kpc, M33 is the only nearby late-type spiral galaxy; it can provide an important link between the cluster populations of earlier-type spirals (Milky Way and M31) and the numerous, nearby later-type dwarf galaxies. A database of star clusters for M33 have been yielded from the ground-based work (Hiltner 1960; Kron & Mayall 1960; Christian & Schommer 1982, 1988; Melnick & D'Odorico 1978; Mochejska et al. 1998) and from the *Hubble Space Telescope* (*HST*) images (Chandar et al. 1999a; Chandar, Bianchi, & Ford 2001). In specific, the *HST* spatial resolution allowed Chandar et al. (1999a, 2001) to penetrate the crowded, spiral regions of M33, yielding the unbiased, representative sample of star clusters, which can be used to probe the global properties of M33. Since clusters at the distance of M33 are easily distinguished from stellar sources in *HST* WFPC2 images, the clusters detected by *HST* WFPC2 images are reliable.

Using the *HST* WFPC2 multiband images of 20 fields in M33, Chandar et al. (1999a) detected 60 star clusters in this spiral galaxy. These clusters sample a variety of environments from outer regions to spiral arms and central regions and are the first unbiased, representative sample of star clusters in M33. Then, Chandar, Bianchi, & Ford (1999b) estimated the ages and masses for these star clusters by comparing the integrated photometric measurements with evolutionary models and theoretical $M/L_V$ ratios. They found the 60 star clusters to form continuously in their parent galaxy from $\sim 4 \times 10^6$ to $10^{10}$ yr and to have masses between $\sim 4 \times 10^2$ and $3 \times 10^5$ $M_\odot$.

M33 was observed as part of galaxy calibration program of the Beijing-Arizona-Taiwan-Connecticut (BATC) Multicolor Sky Survey (Fan et al. 1996; Zheng et al. 1999) from 1995 September 23 to 2000 August 28. This program uses the 60/90 cm Schmidt telescope at the Xinglong Station of Beijing Astronomical Observatory (BAO) and has a custom-designed set of 15 intermediate-band filters to do spectrophotometry for preselected 1 deg$^2$ regions of the northern sky. The BAO Schmidt telescope is equipped with a Ford 2048 × 2048 CCD at its main focus. Using the 13 intermediate-band filters images of M33 obtained from the BATC Multicolor Sky Survey, Ma et al. (2001) studied the 60 star clusters of Chandar et al. (1999a). They (Ma et al. 2001) presented the spectral energy distributions (SEDs) by aperture photometry and estimated the ages by comparing the integrated photometric measurements with theoretical stellar population synthesis models for these star clusters. We can provide the accurate SEDs for these star clusters using the multicolor photometry of BATC.

From 35 deep *HST* WFPC2 fields, Chandar et al. (2001) again detected 102 star clusters in M33, 82 of which had not previously been detected. Using one dereddened color $[(V-I)_0]$, they estimated the ages and masses for these clusters with single stellar population models. However, they did not give quantitative age estimates for individual clusters because of the relatively large uncertainty associated with age estimates from comparison of one color with single stellar population models.

In this paper, we present the SEDs of 78 star clusters that were detected by Chandar et al. (2001) in M33 and quantitatively estimate the ages for these clusters by comparing the integrated photometric measurements with theoretical stellar population synthesis models.

The outline of the paper is as follows: Details of observations and data reduction are given in § 2. In § 3, we provide a

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brief description of the stellar population synthesis models of G. Bruzual & S. Charlot (1996, unpublished). The age estimates for the star clusters 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. (2001), who used 35 deep *HST* WFPC2 fields to extend the search for star clusters in M33 and particularly to focus on detection of older clusters. Since these clusters cover a range of environments from the center to the skirts, they can be used to probe the global properties of the parent galaxy. At the same time, the accurate positions of these star clusters are presented in Chandar et al. (2001). As a result, we select these star clusters to be studied and obtain their SEDs in the 13 intermediate-band filters by aperture photometry. The age estimates for these star clusters are obtained using the theoretical evolutionary population synthesis methods. Clusters 63, 65, 66, 80, 82, 85, 102, 105, 111, 123, 134, 138, 140, 143, and 149 are not included in our sample because of their low signal-to-noise ratio in the images of some BATC filters. In addition, clusters 61, 70, 81, 90, 98, 104, 106, 114, and 116 are U49, M9, C20, U77, R14, H38, H10, C38, and R12 of Christian & Schommer (1982), respectively, the SEDs and ages of which were presented (Ma et al. 2002) and are also not included in our sample. The position of cluster 85 presented by Chandar et al. (2001) may be wrong. It should be R.A. = $01^h33^m14\overset{s}{.}28$, decl. = $30°28'22\overset{''}{.}9$, and it is U137 of Christian & Schommer (1982; see details from Ma et al. 2002).

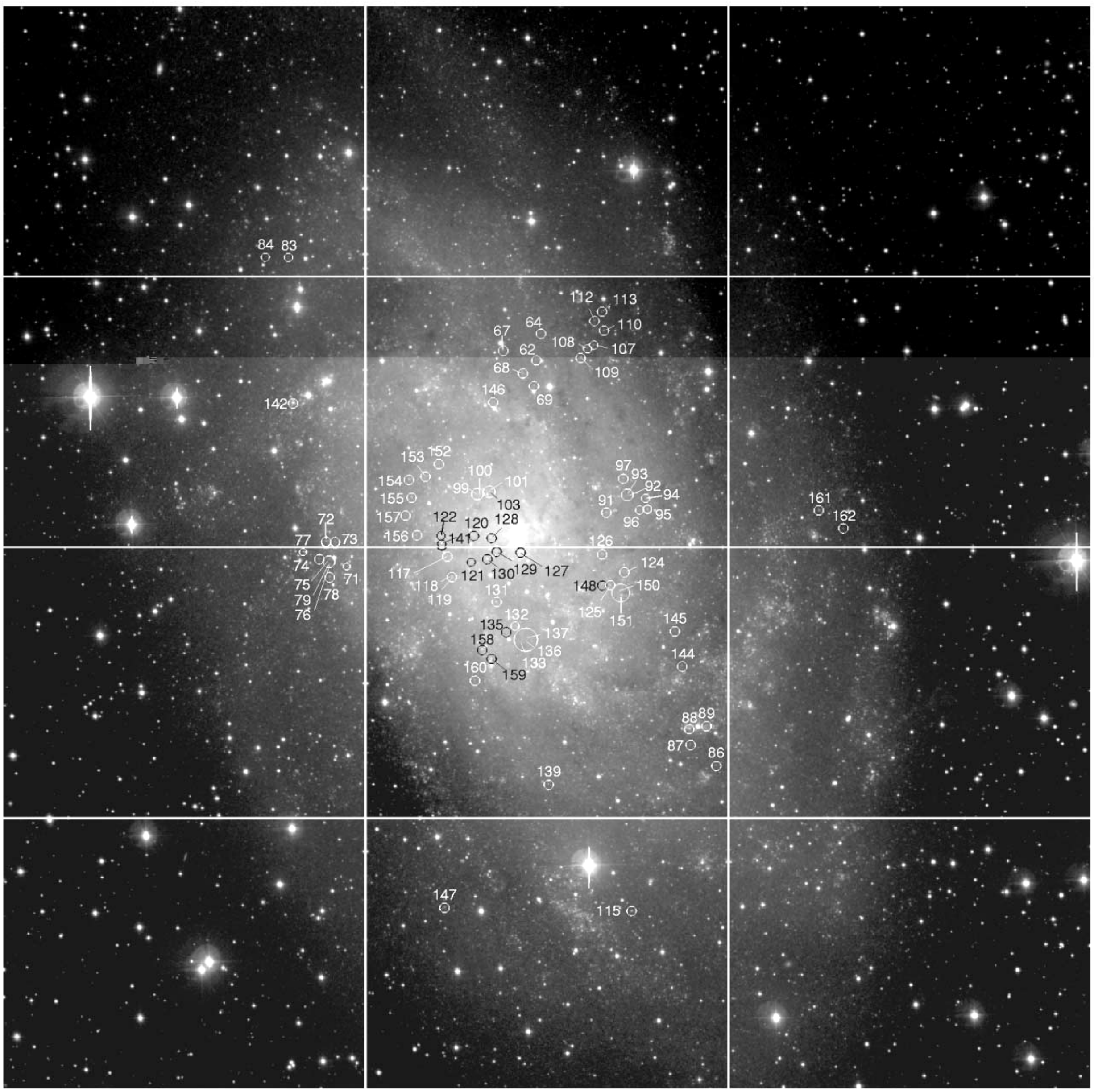



Fig. 1.—Image of M33 in filter BATC07 (5785 Å) and the positions of the sample star clusters. The image size is 52′ × 53′. The center of the image is located at R.A. = $01^h33^m50\overset{s}{.}58$, decl. = $30°39'08\overset{''}{.}4$ (J2000.0). North is up, and east is to the left.

Figure 1 is the image of M33 in filter BATC07 (5785 Å), the circles in which indicate the positions of the sample clusters in this paper.

### 2.2. *Observations and Data Reduction*

The large field multicolor observations of the spiral galaxy M33 were obtained in the BATC photometric system. The multicolor BATC filter system, which was specifically designed to avoid contamination from the brightest and most variable night-sky emission lines, includes 15 intermediate-band filters, covering the total optical wavelength range from 3000 to 10000 Å. The images of M33 covering the whole optical body of M33 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 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 $+26^{\circ}2606$, and BD $+17^{\circ}4708$ were observed during photometric nights (see details from Yan et al. 1999; Zhou et al. 2001b). Column (6) in Table 1 gives the calibration error in magnitudes for the standard stars in each filter. The formal errors we obtain for these stars in the 13 BATC filters are $\lesssim 0.02$ mag. This indicates that we can define the standard BATC system to an accuracy of $\lesssim 0.02$ mag.

The data were reduced with standard procedures, including bias subtraction and flat fielding of the CCD images, with an automatic data reduction software named PIPELINE I developed for the BATC multicolor sky survey (see Ma et al. 2001, 2002 for a detail).

### 2.3. *Integrated Photometry*

For each star cluster, the PHOT routine in DAOPHOT (Stetson 1987, 1992) is 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 the Ford CCDs, is adopted. Aperture corrections are computed using isolated stars. The SEDs in 13 BATC filters for 78 star clusters were obtained. Table 2 contains the following information: Column (1) is cluster number that is taken from Chandar et al. (2001). Column (2)–(14) show the magnitudes of different bands. Second row for each star cluster is the uncertainties of the magnitudes of the corresponding bands. The uncertainties for each filter are given by DAOPHOT.

TABLE 1
PARAMETERS OF THE BATC FILTERS AND STATISTICS OF OBSERVATIONS

| No. (1) | Name (2) | $\lambda$[a] (Å) (3) | Exp. (hr) (4) | $N_{\rm img}$[b] (5) | rms[c] (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 |

[a] Central wavelength for each BATC filter.
[b] Image numbers for each BATC filter.
[c] Calibration error in magnitudes for each filter as obtained from the standard stars.

### 2.4. *Comparison with Previous Photometry*

Using the Landolt standards, Zhou et al. (2001a) presented the relationships between the BATC intermediate-band system and *UBVRI* broadband system from the catalogs of Landolt (1983, 1992) and Galadí-Enríquez, Trullols, & Jordi (2000). We show the coefficients of one relationship in equation (1):

$$m_V = m_{07} + (0.3233 \pm 0.019)(m_{06} - m_{08}) + 0.0590 \pm 0.010 . \quad (1)$$

Using equation (1), we transformed the magnitudes of 78 star clusters in the BATC06, BATC07, and BATC08 bands to ones in the $V$ band. Figure 2 plots the comparison of $V$ (BATC) photometry with previously published measurements (Chandar et al. 2001). Table 3 shows this comparison. The mean $V$ magnitude difference (this paper's values minus the values of Chandar et al. 2001) is $\langle \Delta V \rangle = 0.036 \pm 0.042$. The uncertainties in $V$ (BATC) have been added linearly, i.e., $\sigma_B = \sigma_{07} + 0.3233(\sigma_{06} + \sigma_{08})$, to reflect the error in the three filter measurements. From Figure 2 and Table 3, it can be seen that there is good agreement in the photometric measurements between Chandar et al. (2001) and this paper, except for clusters 115 and 127.

## 3. DATABASES OF SIMPLE STELLAR POPULATIONS

Tinsley (1972) and Searle, Sargent, & Bagnuolo (1973) did the pioneering work in evolutionary population synthesis. This method has become a standard technique for studying 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, as well as 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 from the Padova and Geneva groups (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).

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 1997). SSPs are the basic building blocks of 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 compositions, supplemented with a library of stellar spectra for stars at different evolutionary stages in evolution synthesis models. In this paper, we use the SSPs of Galaxy Isochrone Synthesis Spectra Evolution Library (hereafter GSSP; G. Bruzual &

TABLE 2

SEDs of 78 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) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 62.......... | 19.970 | 19.551 | 19.672 | 19.377 | 19.248 | 19.301 | 19.142 | 19.172 | 18.984 | 18.881 | 19.070 | 18.627 | 19.131 |
| | 0.238 | 0.186 | 0.168 | 0.162 | 0.133 | 0.168 | 0.151 | 0.188 | 0.180 | 0.166 | 0.268 | 0.187 | 0.389 |
| 64.......... | 19.433 | 19.262 | 19.282 | 19.171 | 18.988 | 18.984 | 18.969 | 18.891 | 18.837 | 18.848 | 18.735 | 18.646 | 18.524 |
| | 0.089 | 0.087 | 0.082 | 0.094 | 0.084 | 0.100 | 0.111 | 0.127 | 0.137 | 0.140 | 0.192 | 0.187 | 0.244 |
| 67.......... | 17.742 | 17.563 | 17.559 | 17.470 | 17.456 | 17.469 | 17.414 | 17.402 | 17.435 | 17.293 | 17.288 | 17.396 | 17.208 |
| | 0.034 | 0.033 | 0.032 | 0.039 | 0.032 | 0.034 | 0.037 | 0.044 | 0.052 | 0.049 | 0.060 | 0.068 | 0.068 |
| 68.......... | 17.925 | 17.801 | 17.883 | 17.773 | 17.910 | 17.824 | 17.849 | 17.879 | 17.747 | 17.729 | 17.774 | 17.784 | 17.718 |
| | 0.032 | 0.036 | 0.035 | 0.043 | 0.051 | 0.052 | 0.066 | 0.071 | 0.083 | 0.084 | 0.113 | 0.115 | 0.125 |
| 69.......... | 19.363 | 19.100 | 18.992 | 18.525 | 18.623 | 18.478 | 18.336 | 18.276 | 18.191 | 18.208 | 17.961 | 17.903 | 18.083 |
| | 0.154 | 0.125 | 0.135 | 0.155 | 0.100 | 0.088 | 0.093 | 0.087 | 0.099 | 0.103 | 0.106 | 0.102 | 0.163 |
| 71.......... | 19.640 | 19.258 | 19.241 | 19.131 | 19.054 | 19.065 | 18.974 | 18.977 | 18.887 | 18.928 | 18.931 | 18.535 | 18.705 |
| | 0.205 | 0.135 | 0.105 | 0.134 | 0.097 | 0.131 | 0.125 | 0.134 | 0.146 | 0.145 | 0.233 | 0.138 | 0.220 |
| 72.......... | 18.468 | 18.216 | 18.284 | 18.230 | 18.222 | 18.193 | 18.091 | 18.031 | 17.715 | 17.667 | 17.745 | 17.380 | 17.122 |
| | 0.080 | 0.062 | 0.055 | 0.070 | 0.048 | 0.058 | 0.052 | 0.056 | 0.051 | 0.046 | 0.067 | 0.047 | 0.048 |
| 73.......... | 20.156 | 19.692 | 19.652 | 19.739 | 19.357 | 19.368 | 19.191 | 19.269 | 19.056 | 18.755 | 19.113 | 18.484 | 18.430 |
| | 0.319 | 0.171 | 0.112 | 0.155 | 0.097 | 0.110 | 0.104 | 0.129 | 0.118 | 0.097 | 0.220 | 0.117 | 0.149 |
| 74.......... | 19.926 | 19.425 | 19.138 | 18.868 | 18.678 | 18.589 | 18.465 | 18.399 | 18.410 | 18.164 | 18.281 | 18.094 | 18.081 |
| | 0.201 | 0.142 | 0.095 | 0.100 | 0.064 | 0.069 | 0.064 | 0.068 | 0.072 | 0.061 | 0.098 | 0.076 | 0.101 |
| 75.......... | 19.782 | 19.400 | 19.256 | 18.811 | 19.164 | 19.177 | 19.370 | 19.133 | 19.033 | 19.028 | 18.796 | 18.969 | 18.790 |
| | 0.190 | 0.164 | 0.139 | 0.143 | 0.155 | 0.169 | 0.246 | 0.199 | 0.228 | 0.211 | 0.240 | 0.256 | 0.303 |
| 76.......... | 19.427 | 19.077 | 19.093 | 18.900 | 18.906 | 18.913 | 18.852 | 18.893 | 18.697 | 18.758 | 18.588 | 18.634 | 18.377 |
| | 0.127 | 0.098 | 0.105 | 0.122 | 0.115 | 0.129 | 0.145 | 0.154 | 0.144 | 0.151 | 0.202 | 0.161 | 0.180 |
| 77.......... | 18.534 | 18.327 | 18.353 | 18.037 | 18.080 | 17.995 | 17.819 | 17.816 | 17.635 | 17.497 | 17.572 | 17.464 | 17.093 |
| | 0.061 | 0.045 | 0.039 | 0.046 | 0.032 | 0.036 | 0.030 | 0.036 | 0.035 | 0.028 | 0.049 | 0.037 | 0.054 |
| 78.......... | 18.169 | 18.041 | 18.174 | 18.191 | 18.196 | 18.297 | 18.368 | 18.312 | 18.333 | 18.426 | 18.613 | 18.282 | 18.184 |
| | 0.065 | 0.064 | 0.064 | 0.090 | 0.066 | 0.092 | 0.100 | 0.110 | 0.124 | 0.104 | 0.225 | 0.114 | 0.175 |
| 79.......... | 19.398 | 19.123 | 19.082 | 18.970 | 18.831 | 18.799 | 18.789 | 18.665 | 18.516 | 18.452 | 18.258 | 17.980 | 18.000 |
| | 0.153 | 0.132 | 0.139 | 0.152 | 0.118 | 0.133 | 0.148 | 0.138 | 0.143 | 0.120 | 0.149 | 0.105 | 0.130 |
| 83.......... | 19.602 | 19.485 | 19.652 | 19.422 | 19.523 | 19.388 | 19.405 | 19.166 | 19.233 | 18.962 | 18.900 | 17.760 | 18.561 |
| | 0.106 | 0.099 | 0.100 | 0.104 | 0.092 | 0.103 | 0.109 | 0.108 | 0.114 | 0.097 | 0.148 | 0.055 | 0.214 |
| 84.......... | 20.139 | 20.126 | 20.281 | 20.259 | 19.944 | 20.196 | 20.079 | 20.275 | 20.047 | 20.539 | 20.205 | 20.112 | 19.839 |
| | 0.134 | 0.129 | 0.164 | 0.202 | 0.123 | 0.183 | 0.185 | 0.279 | 0.228 | 0.296 | 0.478 | 0.446 | 0.634 |
| 86.......... | 19.590 | 19.409 | 19.220 | 19.089 | 19.027 | 18.867 | 18.556 | 18.758 | 18.716 | 18.780 | 18.963 | 18.753 | 18.418 |
| | 0.107 | 0.087 | 0.073 | 0.070 | 0.056 | 0.056 | 0.072 | 0.065 | 0.067 | 0.083 | 0.163 | 0.108 | 0.153 |
| 87.......... | 19.913 | 19.440 | 19.219 | 18.963 | 18.888 | 18.684 | 18.533 | 18.450 | 18.497 | 18.348 | 18.188 | 18.234 | 18.276 |
| | 0.143 | 0.090 | 0.060 | 0.057 | 0.045 | 0.051 | 0.051 | 0.052 | 0.055 | 0.047 | 0.072 | 0.075 | 0.102 |
| 88.......... | 17.608 | 17.579 | 17.228 | 17.690 | 17.878 | 17.855 | 17.143 | 17.973 | 18.123 | 18.281 | 18.468 | 17.912 | 18.170 |
| | 0.182 | 0.185 | 0.098 | 0.218 | 0.119 | 0.181 | 0.094 | 0.190 | 0.244 | 0.232 | 0.266 | 0.128 | 0.209 |
| 89.......... | 18.292 | 18.232 | 18.331 | 18.232 | 18.425 | 18.514 | 17.991 | 18.468 | 18.601 | 18.534 | 18.508 | 18.300 | 18.758 |
| | 0.142 | 0.136 | 0.177 | 0.158 | 0.156 | 0.190 | 0.213 | 0.195 | 0.238 | 0.186 | 0.256 | 0.179 | 0.484 |
| 91.......... | 18.517 | 18.203 | 18.047 | 17.933 | 17.743 | 17.750 | 17.569 | 17.596 | 17.579 | 17.416 | 17.556 | 17.447 | 17.358 |
| | 0.092 | 0.074 | 0.060 | 0.056 | 0.042 | 0.045 | 0.051 | 0.042 | 0.046 | 0.043 | 0.059 | 0.062 | 0.076 |
| 92.......... | 18.876 | 18.707 | 18.755 | 18.590 | 18.589 | 18.481 | 18.469 | 18.433 | 18.515 | 18.378 | 18.535 | 18.376 | 18.353 |
| | 0.095 | 0.089 | 0.079 | 0.116 | 0.102 | 0.098 | 0.125 | 0.121 | 0.154 | 0.145 | 0.200 | 0.197 | 0.250 |
| 93.......... | 19.262 | 19.262 | 19.566 | 19.190 | 19.431 | 19.318 | 19.722 | 19.339 | 19.461 | 19.659 | 19.826 | 19.992 | 20.034 |
| | 0.171 | 0.147 | 0.162 | 0.189 | 0.223 | 0.203 | 0.387 | 0.269 | 0.363 | 0.488 | 0.660 | 0.867 | 1.192 |
| 94.......... | 18.533 | 18.374 | 18.544 | 18.382 | 18.469 | 18.420 | 18.382 | 18.364 | 18.255 | 18.239 | 18.313 | 18.079 | 18.165 |
| | 0.059 | 0.060 | 0.064 | 0.068 | 0.062 | 0.076 | 0.074 | 0.090 | 0.099 | 0.092 | 0.119 | 0.109 | 0.174 |
| 95.......... | 18.055 | 17.941 | 17.991 | 17.887 | 17.762 | 17.728 | 17.622 | 17.487 | 17.335 | 17.280 | 17.223 | 17.139 | 16.944 |
| | 0.040 | 0.038 | 0.036 | 0.041 | 0.038 | 0.041 | 0.042 | 0.039 | 0.041 | 0.042 | 0.046 | 0.045 | 0.054 |
| 96.......... | 19.486 | 19.442 | 19.451 | 19.457 | 19.432 | 19.473 | 19.164 | 19.234 | 19.361 | 19.148 | 19.002 | 18.754 | 19.249 |
| | 0.145 | 0.163 | 0.147 | 0.181 | 0.183 | 0.219 | 0.187 | 0.212 | 0.269 | 0.228 | 0.257 | 0.181 | 0.459 |
| 97.......... | 19.183 | 18.805 | 18.641 | 18.486 | 18.293 | 18.168 | 17.825 | 17.793 | 17.723 | 17.607 | 17.532 | 17.369 | 17.444 |
| | 0.125 | 0.105 | 0.091 | 0.086 | 0.067 | 0.068 | 0.063 | 0.059 | 0.069 | 0.057 | 0.065 | 0.056 | 0.094 |
| 99.......... | 19.015 | 18.739 | 18.673 | 18.494 | 18.342 | 18.363 | 18.321 | 18.171 | 17.915 | 17.816 | 17.880 | 17.670 | 17.328 |
| | 0.204 | 0.185 | 0.167 | 0.179 | 0.146 | 0.181 | 0.226 | 0.199 | 0.167 | 0.145 | 0.192 | 0.164 | 0.146 |
| 100........ | 17.161 | 17.057 | 17.137 | 17.160 | 17.172 | 17.307 | 17.342 | 17.371 | 17.529 | 17.575 | 17.569 | 17.901 | 18.167 |
| | 0.036 | 0.039 | 0.043 | 0.052 | 0.049 | 0.059 | 0.099 | 0.085 | 0.113 | 0.120 | 0.141 | 0.207 | 0.339 |
| 101........ | 19.580 | 19.227 | 19.624 | 19.130 | 19.019 | 19.071 | 19.863 | 19.110 | 19.108 | 18.962 | 19.296 | 19.319 | 18.789 |
| | 0.414 | 0.344 | 0.431 | 0.343 | 0.282 | 0.326 | 0.899 | 0.448 | 0.524 | 0.442 | 0.677 | 0.715 | 0.623 |
| 103........ | 19.482 | 19.223 | 19.071 | 18.870 | 18.764 | 18.713 | 19.007 | 18.876 | 19.205 | 18.948 | 18.872 | 19.680 | 20.271 |
| | 0.354 | 0.321 | 0.257 | 0.259 | 0.218 | 0.225 | 0.418 | 0.333 | 0.528 | 0.422 | 0.438 | 0.945 | 2.321 |
| 107........ | 18.788 | 18.541 | 18.507 | 18.462 | 18.378 | 18.395 | 18.229 | 18.273 | 18.119 | 18.037 | 18.070 | 18.003 | 17.890 |
| | 0.070 | 0.059 | 0.049 | 0.060 | 0.044 | 0.049 | 0.053 | 0.058 | 0.059 | 0.061 | 0.084 | 0.084 | 0.119 |

TABLE 2—*Continued*

| 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) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 108........ | 19.316 | 19.304 | 19.268 | 19.017 | 19.215 | 19.055 | 19.091 | 19.046 | 18.948 | 18.775 | 18.952 | 18.904 | 18.524 |
| | 0.188 | 0.178 | 0.124 | 0.140 | 0.133 | 0.118 | 0.151 | 0.152 | 0.146 | 0.140 | 0.212 | 0.174 | 0.200 |
| 109........ | 17.991 | 17.778 | 17.812 | 17.777 | 17.727 | 17.726 | 17.692 | 17.658 | 17.605 | 17.498 | 17.608 | 17.392 | 17.472 |
| | 0.049 | 0.044 | 0.042 | 0.054 | 0.044 | 0.054 | 0.053 | 0.058 | 0.063 | 0.056 | 0.074 | 0.059 | 0.090 |
| 110........ | 19.262 | 18.791 | 18.784 | 18.594 | 18.506 | 18.497 | 18.480 | 18.440 | 18.391 | 18.358 | 18.232 | 18.295 | 18.385 |
| | 0.087 | 0.067 | 0.057 | 0.048 | 0.048 | 0.046 | 0.052 | 0.055 | 0.066 | 0.073 | 0.083 | 0.086 | 0.190 |
| 112........ | 19.082 | 18.794 | 18.735 | 18.508 | 18.485 | 18.396 | 18.330 | 18.332 | 18.221 | 18.036 | 18.078 | 18.071 | 18.168 |
| | 0.082 | 0.071 | 0.059 | 0.063 | 0.053 | 0.056 | 0.059 | 0.065 | 0.071 | 0.063 | 0.080 | 0.082 | 0.161 |
| 113........ | 19.868 | 19.545 | 19.527 | 19.685 | 19.362 | 19.618 | 19.706 | 19.577 | 19.689 | 19.498 | 19.968 | 20.229 | 20.099 |
| | 0.109 | 0.074 | 0.068 | 0.089 | 0.066 | 0.083 | 0.101 | 0.122 | 0.146 | 0.142 | 0.324 | 0.438 | 0.812 |
| 115........ | 17.867 | 17.660 | 17.796 | 17.740 | 17.836 | 17.857 | 17.920 | 17.798 | 17.940 | 17.874 | 17.975 | 17.971 | 17.635 |
| | 0.023 | 0.018 | 0.018 | 0.020 | 0.019 | 0.023 | 0.027 | 0.029 | 0.038 | 0.039 | 0.055 | 0.063 | 0.078 |
| 117........ | 19.060 | 18.904 | 18.837 | 18.710 | 18.726 | 18.790 | 18.718 | 18.741 | 18.765 | 18.636 | 18.809 | 18.355 | 18.748 |
| | 0.164 | 0.160 | 0.132 | 0.149 | 0.156 | 0.177 | 0.196 | 0.213 | 0.252 | 0.228 | 0.362 | 0.253 | 0.433 |
| 118........ | 18.322 | 18.002 | 17.883 | 17.658 | 17.515 | 17.387 | 17.274 | 17.129 | 17.049 | 17.104 | 16.974 | 16.722 | 16.782 |
| | 0.163 | 0.154 | 0.123 | 0.126 | 0.091 | 0.094 | 0.087 | 0.084 | 0.084 | 0.084 | 0.089 | 0.066 | 0.089 |
| 119........ | 18.481 | 18.162 | 18.088 | 17.866 | 17.719 | 17.599 | 17.540 | 17.336 | 17.262 | 17.306 | 17.163 | 16.898 | 16.947 |
| | 0.160 | 0.154 | 0.122 | 0.126 | 0.093 | 0.094 | 0.096 | 0.082 | 0.086 | 0.081 | 0.086 | 0.063 | 0.089 |
| 120........ | 18.281 | 17.983 | 18.108 | 18.002 | 18.041 | 18.003 | 18.165 | 18.019 | 18.252 | 18.369 | 18.309 | 19.015 | 19.853 |
| | 0.261 | 0.236 | 0.234 | 0.280 | 0.234 | 0.276 | 0.309 | 0.308 | 0.427 | 0.429 | 0.470 | 0.904 | 2.539 |
| 121........ | 18.602 | 18.290 | 18.297 | 18.184 | 18.466 | 18.422 | 17.962 | 18.808 | 19.161 | 19.213 | 19.548 | 19.123 | 20.396 |
| | 0.189 | 0.148 | 0.139 | 0.137 | 0.147 | 0.154 | 0.189 | 0.221 | 0.370 | 0.412 | 0.739 | 0.600 | 2.042 |
| 122........ | 17.297 | 17.137 | 17.189 | 17.132 | 17.025 | 17.054 | 17.125 | 17.010 | 17.031 | 16.954 | 16.881 | 16.804 | 16.758 |
| | 0.165 | 0.145 | 0.129 | 0.144 | 0.096 | 0.123 | 0.200 | 0.155 | 0.186 | 0.134 | 0.146 | 0.135 | 0.191 |
| 124........ | 18.820 | 18.849 | 19.003 | 18.906 | 19.068 | 19.208 | 19.177 | 19.057 | 18.998 | 19.262 | 19.231 | 19.251 | 18.488 |
| | 0.144 | 0.161 | 0.155 | 0.173 | 0.163 | 0.208 | 0.218 | 0.194 | 0.189 | 0.276 | 0.293 | 0.324 | 0.239 |
| 125........ | 18.412 | 18.348 | 18.463 | 18.429 | 18.485 | 18.500 | 18.520 | 18.491 | 18.812 | 18.746 | 18.457 | 18.364 | 18.855 |
| | 0.134 | 0.157 | 0.160 | 0.192 | 0.183 | 0.220 | 0.258 | 0.273 | 0.423 | 0.368 | 0.309 | 0.277 | 0.588 |
| 126........ | 20.649 | 19.648 | 19.545 | 19.327 | 18.988 | 18.935 | 19.072 | 18.551 | 18.416 | 18.252 | 18.116 | 17.992 | 18.019 |
| | 0.876 | 0.393 | 0.362 | 0.366 | 0.223 | 0.235 | 0.312 | 0.190 | 0.188 | 0.151 | 0.153 | 0.146 | 0.181 |
| 127........ | 15.712 | 15.650 | 15.796 | 15.767 | 15.971 | 15.950 | 15.990 | 15.966 | 15.994 | 16.108 | 16.167 | 16.250 | 16.078 |
| | 0.035 | 0.037 | 0.038 | 0.044 | 0.065 | 0.070 | 0.104 | 0.095 | 0.104 | 0.107 | 0.126 | 0.139 | 0.148 |
| 128........ | 18.885 | 18.545 | 18.441 | 18.464 | 18.246 | 18.375 | 18.286 | 18.155 | 17.886 | 17.819 | 17.829 | 17.690 | 17.531 |
| | 0.429 | 0.352 | 0.268 | 0.367 | 0.263 | 0.342 | 0.327 | 0.330 | 0.298 | 0.268 | 0.291 | 0.281 | 0.296 |
| 129........ | 18.234 | 18.107 | 18.174 | 18.193 | 17.865 | 18.039 | 18.037 | 17.910 | 17.675 | 17.642 | 17.357 | 17.286 | 17.284 |
| | 0.204 | 0.214 | 0.203 | 0.280 | 0.159 | 0.235 | 0.276 | 0.261 | 0.236 | 0.213 | 0.167 | 0.177 | 0.204 |
| 130........ | 17.671 | 17.323 | 17.481 | 17.221 | 17.431 | 17.063 | 16.851 | 16.810 | 16.780 | 17.125 | 16.663 | 16.678 | 16.598 |
| | 0.089 | 0.078 | 0.079 | 0.089 | 0.087 | 0.080 | 0.066 | 0.075 | 0.086 | 0.114 | 0.087 | 0.093 | 0.108 |
| 131........ | 18.270 | 17.870 | 17.868 | 17.746 | 17.539 | 17.479 | 17.316 | 17.315 | 17.320 | 17.336 | 17.205 | 17.238 | 17.084 |
| | 0.113 | 0.089 | 0.074 | 0.079 | 0.052 | 0.054 | 0.049 | 0.052 | 0.061 | 0.058 | 0.069 | 0.077 | 0.085 |
| 132........ | 18.892 | 18.955 | 18.947 | 18.861 | 18.929 | 18.856 | 18.697 | 18.647 | 18.495 | 18.548 | 18.492 | 18.581 | 18.247 |
| | 0.211 | 0.216 | 0.187 | 0.203 | 0.170 | 0.174 | 0.176 | 0.182 | 0.172 | 0.180 | 0.227 | 0.256 | 0.256 |
| 133........ | 18.650 | 18.490 | 18.531 | 18.497 | 18.402 | 18.395 | 18.242 | 18.170 | 18.113 | 18.064 | 17.988 | 17.981 | 17.860 |
| | 0.123 | 0.127 | 0.124 | 0.162 | 0.117 | 0.135 | 0.123 | 0.124 | 0.127 | 0.114 | 0.136 | 0.127 | 0.157 |
| 135........ | 19.484 | 19.079 | 19.000 | 19.412 | 19.010 | 18.905 | 18.500 | 18.947 | 18.643 | 18.708 | 18.632 | 18.785 | 18.347 |
| | 0.355 | 0.290 | 0.226 | 0.425 | 0.236 | 0.220 | 0.153 | 0.258 | 0.188 | 0.248 | 0.261 | 0.356 | 0.294 |
| 136........ | 19.374 | 19.079 | 19.099 | 18.960 | 18.877 | 18.905 | 18.869 | 18.865 | 18.835 | 18.719 | 18.731 | 18.949 | 18.561 |
| | 0.213 | 0.216 | 0.201 | 0.236 | 0.187 | 0.224 | 0.205 | 0.242 | 0.258 | 0.221 | 0.275 | 0.342 | 0.303 |
| 137........ | 18.374 | 18.095 | 18.196 | 18.136 | 18.121 | 18.130 | 18.066 | 18.137 | 18.138 | 18.090 | 18.139 | 17.906 | 18.133 |
| | 0.072 | 0.065 | 0.067 | 0.074 | 0.064 | 0.075 | 0.082 | 0.090 | 0.103 | 0.101 | 0.140 | 0.106 | 0.188 |
| 139........ | 18.633 | 18.520 | 18.578 | 18.535 | 18.458 | 18.413 | 18.351 | 18.317 | 18.227 | 18.332 | 18.352 | 17.962 | 18.158 |
| | 0.069 | 0.062 | 0.063 | 0.066 | 0.056 | 0.061 | 0.067 | 0.069 | 0.072 | 0.082 | 0.116 | 0.079 | 0.149 |
| 141........ | 16.069 | 15.987 | 16.128 | 16.155 | 16.240 | 16.306 | 16.371 | 16.357 | 16.419 | 16.395 | 16.284 | 16.346 | 16.396 |
| | 0.033 | 0.043 | 0.041 | 0.051 | 0.041 | 0.052 | 0.078 | 0.064 | 0.075 | 0.067 | 0.071 | 0.071 | 0.094 |
| 142........ | 15.743 | 15.699 | 15.809 | 15.800 | 15.863 | 15.856 | 15.761 | 15.617 | 15.451 | 15.305 | 15.310 | 15.184 | 14.932 |
| | 0.012 | 0.011 | 0.010 | 0.014 | 0.010 | 0.011 | 0.012 | 0.010 | 0.009 | 0.007 | 0.009 | 0.008 | 0.009 |
| 144........ | 19.991 | 19.810 | 19.717 | 19.464 | 19.386 | 19.214 | 18.917 | 19.089 | 19.036 | 19.060 | 19.145 | 19.179 | 19.271 |
| | 0.280 | 0.216 | 0.187 | 0.175 | 0.124 | 0.123 | 0.125 | 0.143 | 0.130 | 0.126 | 0.239 | 0.206 | 0.391 |
| 145........ | 20.109 | 19.798 | 19.680 | 19.592 | 19.385 | 19.249 | 19.422 | 19.360 | 19.483 | 19.586 | 19.931 | 19.743 | 21.150 |
| | 0.255 | 0.202 | 0.169 | 0.188 | 0.136 | 0.141 | 0.179 | 0.192 | 0.238 | 0.285 | 0.452 | 0.431 | 2.438 |
| 146........ | 18.574 | 18.249 | 18.294 | 18.135 | 18.350 | 18.303 | 18.350 | 18.470 | 18.363 | 18.436 | 18.446 | 18.493 | 18.114 |
| | 0.278 | 0.245 | 0.235 | 0.272 | 0.246 | 0.273 | 0.393 | 0.357 | 0.387 | 0.358 | 0.432 | 0.426 | 0.328 |
| 147........ | 18.439 | 18.360 | 18.441 | 18.356 | 18.420 | 18.419 | 18.328 | 18.393 | 18.521 | 18.541 | 18.809 | 18.709 | 18.733 |
| | 0.033 | 0.031 | 0.027 | 0.027 | 0.026 | 0.033 | 0.031 | 0.042 | 0.046 | 0.060 | 0.134 | 0.100 | 0.181 |
| 148........ | 18.016 | 17.901 | 17.520 | 18.051 | 18.136 | 18.184 | 17.009 | 18.122 | 18.111 | 18.200 | 18.618 | 17.935 | 18.093 |

TABLE 2—*Continued*

| 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) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0.076 | 0.072 | 0.041 | 0.068 | 0.072 | 0.081 | 0.040 | 0.108 | 0.119 | 0.130 | 0.238 | 0.134 | 0.207 |
| 150........ | 17.541 | 17.380 | 17.432 | 17.361 | 17.408 | 17.432 | 17.426 | 17.410 | 17.444 | 17.470 | 17.575 | 17.479 | 17.491 |
| | 0.064 | 0.062 | 0.053 | 0.070 | 0.067 | 0.079 | 0.085 | 0.093 | 0.104 | 0.101 | 0.128 | 0.119 | 0.147 |
| 151........ | 17.717 | 17.493 | 17.502 | 17.390 | 17.333 | 17.305 | 17.257 | 17.200 | 17.152 | 17.097 | 17.067 | 16.968 | 16.941 |
| | 0.063 | 0.063 | 0.055 | 0.067 | 0.054 | 0.061 | 0.062 | 0.062 | 0.064 | 0.059 | 0.068 | 0.063 | 0.080 |
| 152........ | 19.190 | 18.928 | 18.904 | 18.942 | 18.840 | 18.901 | 18.746 | 18.870 | 18.701 | 18.730 | 18.806 | 18.683 | 18.534 |
| | 0.137 | 0.130 | 0.128 | 0.156 | 0.125 | 0.148 | 0.145 | 0.177 | 0.163 | 0.171 | 0.249 | 0.206 | 0.264 |
| 153........ | 18.949 | 18.733 | 18.681 | 18.616 | 18.538 | 18.549 | 18.387 | 18.491 | 18.573 | 18.362 | 18.095 | 18.405 | 18.038 |
| | 0.132 | 0.129 | 0.125 | 0.116 | 0.105 | 0.104 | 0.141 | 0.113 | 0.139 | 0.126 | 0.127 | 0.175 | 0.162 |
| 154........ | 17.890 | 17.734 | 17.789 | 17.698 | 17.718 | 17.713 | 17.575 | 17.611 | 17.569 | 17.512 | 17.407 | 17.338 | 17.323 |
| | 0.045 | 0.041 | 0.040 | 0.045 | 0.040 | 0.047 | 0.066 | 0.055 | 0.067 | 0.062 | 0.067 | 0.062 | 0.107 |
| 155........ | 17.677 | 17.509 | 17.548 | 17.530 | 17.478 | 17.503 | 17.501 | 17.539 | 17.504 | 17.467 | 17.533 | 17.428 | 17.529 |
| | 0.030 | 0.028 | 0.028 | 0.036 | 0.032 | 0.036 | 0.041 | 0.049 | 0.058 | 0.057 | 0.083 | 0.076 | 0.103 |
| 156........ | 18.492 | 18.356 | 18.375 | 18.248 | 18.267 | 18.233 | 18.327 | 18.297 | 18.387 | 18.350 | 18.244 | 18.218 | 18.651 |
| | 0.101 | 0.111 | 0.102 | 0.116 | 0.104 | 0.109 | 0.132 | 0.135 | 0.153 | 0.149 | 0.171 | 0.164 | 0.282 |
| 157........ | 20.023 | 19.557 | 19.483 | 19.239 | 19.180 | 19.180 | 19.181 | 19.103 | 19.149 | 19.052 | 19.202 | 19.499 | 18.769 |
| | 0.401 | 0.310 | 0.247 | 0.264 | 0.210 | 0.229 | 0.258 | 0.247 | 0.303 | 0.266 | 0.370 | 0.532 | 0.301 |
| 158........ | 15.950 | 15.913 | 15.947 | 16.070 | 16.158 | 16.146 | 15.869 | 16.074 | 15.849 | 15.869 | 15.813 | 15.508 | 15.466 |
| | 0.044 | 0.050 | 0.045 | 0.065 | 0.051 | 0.058 | 0.057 | 0.059 | 0.055 | 0.048 | 0.054 | 0.043 | 0.046 |
| 159........ | 16.699 | 16.684 | 16.909 | 16.777 | 17.034 | 16.943 | 16.937 | 16.984 | 16.903 | 17.134 | 16.907 | 16.910 | 16.877 |
| | 0.034 | 0.032 | 0.035 | 0.036 | 0.035 | 0.036 | 0.056 | 0.049 | 0.052 | 0.056 | 0.063 | 0.064 | 0.083 |
| 160........ | 18.762 | 18.558 | 18.638 | 18.565 | 18.521 | 18.452 | 18.495 | 18.332 | 18.366 | 18.334 | 18.042 | 18.183 | 18.043 |
| | 0.098 | 0.088 | 0.082 | 0.091 | 0.072 | 0.079 | 0.098 | 0.082 | 0.090 | 0.091 | 0.110 | 0.119 | 0.135 |
| 161........ | 19.364 | 19.028 | 18.869 | 18.660 | 18.457 | 18.339 | 18.180 | 18.074 | 17.956 | 17.942 | 17.951 | 17.631 | 17.631 |
| | 0.077 | 0.054 | 0.039 | 0.034 | 0.033 | 0.033 | 0.034 | 0.036 | 0.035 | 0.038 | 0.059 | 0.043 | 0.078 |
| 162........ | 20.196 | 20.274 | 20.054 | 19.939 | 19.828 | 19.798 | 19.283 | 19.342 | 19.375 | 19.258 | 19.030 | 19.141 | 18.773 |
| | 0.130 | 0.106 | 0.095 | 0.089 | 0.078 | 0.087 | 0.097 | 0.080 | 0.089 | 0.087 | 0.143 | 0.135 | 0.168 |

S. Charlot 1996, unpublished) to estimate the ages of the sample clusters, since they are simple and reasonably well understood.

### 3.1. *SED of GSSPs*

Charlot & Bruzual (1991) developed a model of stellar population synthesis. In this model, the population synthesis method can be used to determine the distribution of stars in the theoretical color-magnitude diagram for any stellar system. Bruzual & Charlot (1993) presented "isochrone synthesis" as a natural and reliable approach for modeling the evolution of stellar populations in star clusters and galaxies. With this isochrone synthesis algorithm, Bruzual & Charlot (1993) computed the SEDs of stellar populations with solar metallicity. G. Bruzual & S. Charlot (1996, unpublished) improved 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, which are $Z = 0.0004$, 0.004, 0.008, 0.02, 0.05, and 0.1 (see Ma et al. 2001, 2002 for details).

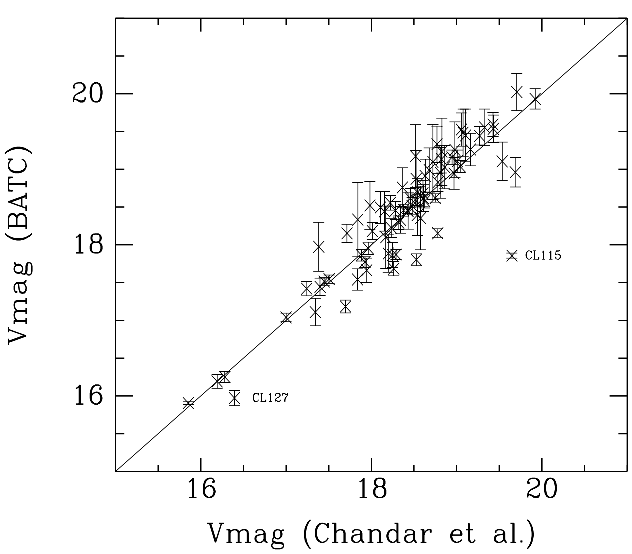



FIG. 2.—Comparison of cluster photometry with previous measurements (*HST*).

### 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 estimate the ages for the sample clusters in this paper, we follow the method of Kong et al. (2000). As we know, the observational data are integrated luminosities. As a result, we need to convolve the SED of GSSP with BATC filter profiles to obtain the optical and near-infrared integrated luminosities for comparison (Kong et al. 2000). The integrated luminosity $L_{\lambda_i}(t, Z)$ of the $i$th BATC filter can be calculated with

$$L_{\lambda_i}(t, Z) = \frac{\int F_\lambda(t, Z)\varphi_i(\lambda)d\lambda}{\int \varphi_i(\lambda)d\lambda} , \qquad (2)$$

where $F_\lambda(t,Z)$ is the SED of the GSSP of metallicity $Z$ at age $t$, and $\varphi_i(\lambda)$ is the response function of the $i$th filter of the BATC filter system ($i = 3$, 4, ..., 15), respectively. For avoiding to use the parameters that are dependent on the

TABLE 3
Comparison of Cluster Photometry with Previous Measurements

| No. | $V$ (Chandar et al.) | $V$(BATC) | No. | $V$ (Chandar et al.) | $V$(BATC) |
|---|---|---|---|---|---|
| 62 | 18.769 ± 0.005 | 19.332 ± 0.240 | 118 | 17.945 ± 0.005 | 17.662 ± 0.162 |
| 64 | 19.007 ± 0.008 | 19.107 ± 0.147 | 119 | 18.247 ± 0.006 | 17.864 ± 0.164 |
| 67 | 17.446 ± 0.002 | 17.515 ± 0.056 | 120 | 18.169 ± 0.000 | 18.100 ± 0.414 |
| 68 | 17.963 ± 0.003 | 17.953 ± 0.082 | 121 | 18.431 ± 0.010 | 18.448 ± 0.241 |
| 69 | 18.541 ± 0.005 | 18.697 ± 0.179 | 122 | 17.343 ± 0.004 | 17.109 ± 0.182 |
| 71 | 18.822 ± 0.004 | 19.134 ± 0.183 | 124 | 18.859 ± 0.009 | 19.029 ± 0.286 |
| 72 | 18.321 ± 0.003 | 18.293 ± 0.089 | 125 | 17.983 ± 0.005 | 18.521 ± 0.316 |
| 73 | 19.430 ± 0.007 | 19.536 ± 0.183 | 126 | 18.518 ± 0.007 | 19.174 ± 0.417 |
| 74 | 18.780 ± 0.003 | 18.827 ± 0.119 | 127 | 16.394 ± 0.003 | 15.971 ± 0.102 |
| 75 | 19.534 ± 0.007 | 19.105 ± 0.256 | 128 | 17.841 ± 0.010 | 18.334 ± 0.492 |
| 76 | 19.687 ± 0.000 | 18.961 ± 0.196 | 129 | 17.383 ± 0.006 | 17.974 ± 0.325 |
| 77 | 18.778 ± 0.003 | 18.153 ± 0.059 | 130 | 17.838 ± 0.006 | 17.541 ± 0.142 |
| 78 | 18.238 ± 0.003 | 18.221 ± 0.125 | 131 | 18.262 ± 0.007 | 17.684 ± 0.095 |
| 79 | 18.969 ± 0.005 | 18.945 ± 0.210 | 132 | 18.678 ± 0.014 | 18.990 ± 0.292 |
| 83 | 19.426 ± 0.006 | 19.593 ± 0.159 | 133 | 18.106 ± 0.006 | 18.494 ± 0.213 |
| 84 | 19.705 ± 0.006 | 20.023 ± 0.247 | 135 | 18.826 ± 0.013 | 19.233 ± 0.445 |
| 86 | 18.945 ± 0.004 | 19.158 ± 0.097 | 136 | 18.807 ± 0.011 | 18.954 ± 0.336 |
| 87 | 19.041 ± 0.006 | 19.037 ± 0.080 | 137 | 18.011 ± 0.006 | 18.182 ± 0.112 |
| 88 | 18.198 ± 0.003 | 17.884 ± 0.248 | 139 | 18.223 ± 0.004 | 18.556 ± 0.097 |
| 89 | 18.538 ± 0.004 | 18.393 ± 0.269 | 141 | 16.281 ± 0.002 | 16.250 ± 0.074 |
| 91 | 17.886 ± 0.003 | 17.861 ± 0.075 | 142 | 15.854 ± 0.001 | 15.904 ± 0.018 |
| 92 | 18.605 ± 0.008 | 18.683 ± 0.171 | 144 | 19.055 ± 0.014 | 19.526 ± 0.220 |
| 93 | 19.105 ± 0.014 | 19.449 ± 0.350 | 145 | 19.329 ± 0.016 | 19.555 ± 0.242 |
| 94 | 18.478 ± 0.005 | 18.516 ± 0.109 | 146 | 18.577 ± 0.012 | 18.355 ± 0.422 |
| 95 | 18.289 ± 0.004 | 17.872 ± 0.065 | 147 | 18.423 ± 0.007 | 18.459 ± 0.045 |
| 96 | 19.075 ± 0.009 | 19.486 ± 0.312 | 148 | 17.714 ± 0.006 | 18.152 ± 0.120 |
| 97 | 18.283 ± 0.006 | 18.455 ± 0.117 | 150 | 17.398 ± 0.004 | 17.444 ± 0.115 |
| 99 | 18.154 ± 0.006 | 18.443 ± 0.262 | 151 | 17.242 ± 0.004 | 17.419 ± 0.095 |
| 100 | 17.697 ± 0.007 | 17.183 ± 0.085 | 152 | 18.632 ± 0.009 | 18.912 ± 0.223 |
| 101 | 18.721 ± 0.012 | 19.097 ± 0.498 | 153 | 18.610 ± 0.009 | 18.619 ± 0.176 |
| 103 | 18.525 ± 0.011 | 18.874 ± 0.374 | 154 | 17.924 ± 0.005 | 17.772 ± 0.070 |
| 107 | 18.378 ± 0.003 | 18.459 ± 0.079 | 155 | 17.504 ± 0.003 | 17.546 ± 0.055 |
| 108 | 19.162 ± 0.006 | 19.262 ± 0.216 | 156 | 18.341 ± 0.008 | 18.331 ± 0.177 |
| 109 | 18.527 ± 0.000 | 17.802 ± 0.079 | 157 | 18.979 ± 0.012 | 19.258 ± 0.369 |
| 110 | 18.515 ± 0.003 | 18.596 ± 0.078 | 158 | 16.191 ± 0.002 | 16.192 ± 0.091 |
| 112 | 18.625 ± 0.004 | 18.580 ± 0.091 | 159 | 17.000 ± 0.003 | 17.039 ± 0.058 |
| 113 | 19.269 ± 0.006 | 19.443 ± 0.122 | 160 | 18.458 ± 0.007 | 18.617 ± 0.127 |
| 115 | 19.648 ± 0.007 | 17.857 ± 0.033 | 161 | 18.749 ± 0.005 | 18.620 ± 0.055 |
| 117 | 18.363 ± 0.006 | 18.759 ± 0.261 | 162 | 19.920 ± 0.014 | 19.933 ± 0.135 |

distance. We calculate the integrated colors of a GSSP relative to the BATC filter BATC08 ($\lambda = 6075$ Å):

$$C_{\lambda_i}(t, Z) = L_{\lambda_i}(t, Z)/L_{6075}(t, Z) . \quad (3)$$

As a result, we obtained the intermediate-band colors of a GSSP for six metallicities from $Z = 0.0004$ to 0.1 using equations (2) and (3).

## 4. AGE ESTIMATES

In order to obtain intrinsic colors of 78 clusters and hence accurate ages the photometric measurements must be dereddened. As Chandar et al. (2001) did, we adopted $E(B-V) = 0.10$. In addition, we adopted the extinction curve presented by Zombeck (1990). An extinction correction $A_\lambda = R_\lambda E(B-V)$ was applied; here $R_\lambda$ is obtained by interpolating using the data of Zombeck (1990).

Since we model the stellar populations of the star clusters by SSPs, the intrinsic colors for each star cluster are determined by two parameters: age and metallicity. We will determine the ages and best-fitted models of metallicity for these star clusters simultaneously by a least-squares method. The age and best-fitted model of metallicity are found by minimizing the difference between the intrinsic and integrated colors of GSSP:

$$R^2(n, t, Z) = \sum_{i=3}^{15} [C_{\lambda_i}^{\rm intr}(n) - C_{\lambda_i}^{\rm ssp}(t, Z)]^2 , \quad (4)$$

where $C_{\lambda_i}^{\rm ssp}(t, Z)$ represents the integrated color in the $i$th filter of a SSP at age $t$ in the model of metallicity $Z$ and $C_{\lambda_i}^{\rm intr}(n)$ is the intrinsic integrated color for $n$th star cluster. Using the stellar evolutionary models (Bertelli et al. 1994) and published line indices of 22 M33 older clusters, Chandar et al. (1999b) narrowed the range of cluster metallicities ($Z$) to be from ~0.0002 to 0.03. As a result, we only select

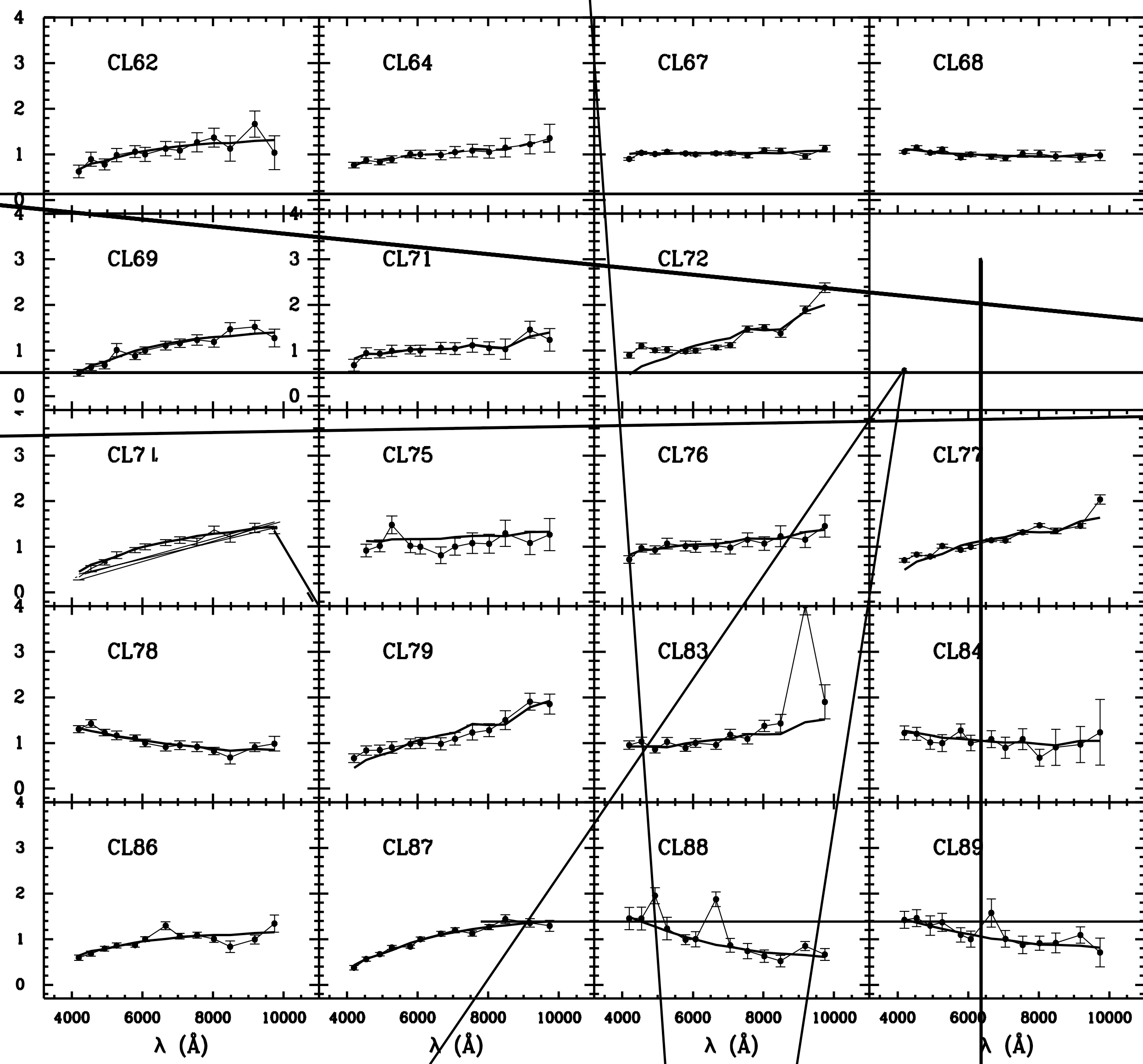


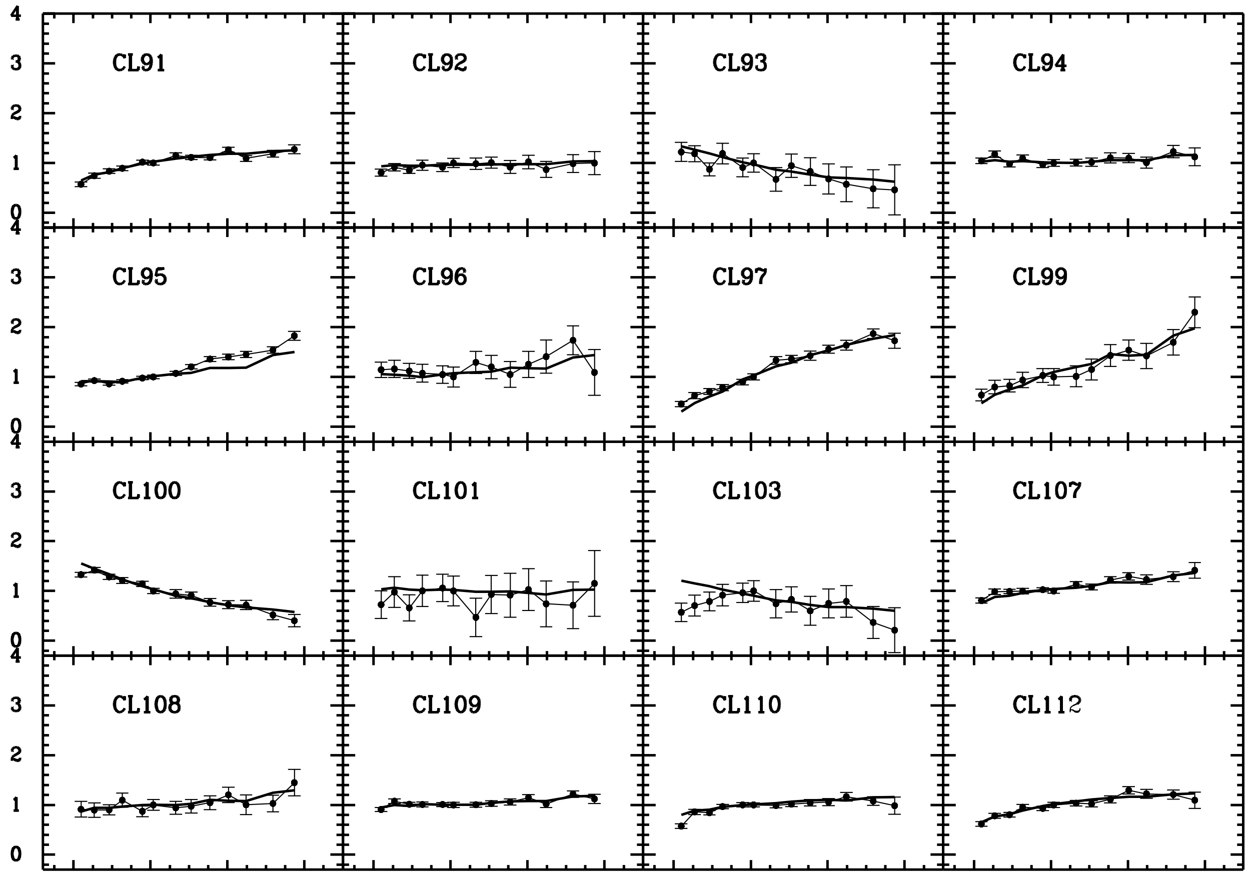

FIG. 3.—Map of the best fit of the integrated color of a SSP with intrinsic integrated color for 78 star clusters. The thick line represents the integrated color of a SSP, and the filled circle represents the intrinsic integrated color of a star cluster.

the models of three metallicities, 0.0004, 0.004, and 0.02 from GSSP.

Figure 3 shows the map of the best fit of the integrated color of a SSP with the intrinsic integrated color for 78 star clusters, and Table 4 presents the best-fitted models of metallicities and ages for these star clusters. In Figure 3, the thick line represents the integrated color of a SSP of GSSP, and the filled circle represents the intrinsic integrated color of a star cluster. From this figure, we see that clusters 83, 88, and 148 have strong emission lines. In the process of fitting, we did not use the strong emission lines.

Figure 4 presents a histogram of cluster ages. The results show that, in general, M33 clusters have been forming continuously, with ages of $\sim 3 \times 10^6$–$10^{10}$ yr. This conclusion confirms the results of Chandar, Bianchi, & Ford (2001). There exist three groups of clusters that formed with three models of metallicities, $Z = 0.02$, 0.004, and 0.0004. In different models of metallicities, the distribution of cluster ages is a little different too. In the model of $Z = 0.02$, the ages of most clusters are younger than $\sim 10^9$ yr, and there are two peaks at $\sim 10^7$ and $\sim 10^9$ yr. In the model of $Z = 0.004$, the clusters formed from $\sim 3 \times 10^6$ to $10^{10}$ yr, and the distribution of ages is more homogeneous than in the other two models. In the model of $Z = 0.0004$, the most clusters formed from $\sim 10^8$ to $10^{10}$ yr. Clusters 97, 106, and 162 have derived ages consistent with that of the globular clusters of the Milky Way, $\sim 1.5 \times 10^{10}$ yr. This result is also consistent with that found by Chandar, Bianchi, & Ford (1999b) and Ma et al. (2001), who presented clusters 11, 28, 29, and 57 to be as old as $\sim 1.5 \times 10^{10}$ yr.

In this section, we estimate the ages of our sample clusters by comparing the photometry of each object with the theoretical stellar population synthesis models for different values of metallicity. However, we want to emphasize that, for




clusters older than several $10^8$ yr, the age/metallicity degeneracy becomes pronounced. In this case, we only mean that in some models of metallicity, the intrinsic integrated color of a cluster can give the best fit with the integrated color of a SSP at some age. In addition, the uncertainties in the age estimates arising from photometric uncertainties are 0.2 or so, i.e., age $\pm$ 0.2 $\times$ age (log yr).

## 5. SUMMARY AND DISCUSSION

In this paper, we have, for the first time, obtained the SEDs of 78 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 BAO 60/90 cm Schmidt telescope in 13 intermediate-band filters from 3800 to 10000 Å, we obtained the SEDs of 78 star clusters that were detected by Chandar et al. (2001).

2. By comparing the integrated photometric measurements with theoretical stellar population synthesis models, we find that clusters formed continuously in M33 from $\sim 3 \times 10^6$ to $10^{10}$ yr. The results also show that there are two peaks at $\sim 8 \times 10^6$ and $\sim 10^9$ yr.

Chandar et al. (1999a, 1999b) estimated ages for 60 star clusters in M33 by comparing the photometric measurements to integrated color from theoretical models by Bertelli et al. (1994). Their results showed that the integrated colors of star clusters depend mostly on age, with a secondary dependence on chemical composition. As a result, we can estimate ages of clusters but cannot determine metallicities of clusters exactly. As Chandar, Bianchi, & Ford (1999b, 2001) and Chandar et al. (1999c) did, we also estimated the ages of our sample clusters by comparing the photometry of each object with models for different values of metallicity. Although we presented the metallicity of each cluster in Table 4, we only mean that, in this model of metallicity, the intrinsic integrated color of each cluster can do the best fit with the integrated color of a SSP.

With spectrophotometry, Christian & Schommer (1983) obtained the ages of the star clusters in M33 to be $\sim 10^7$–$10^{10}$

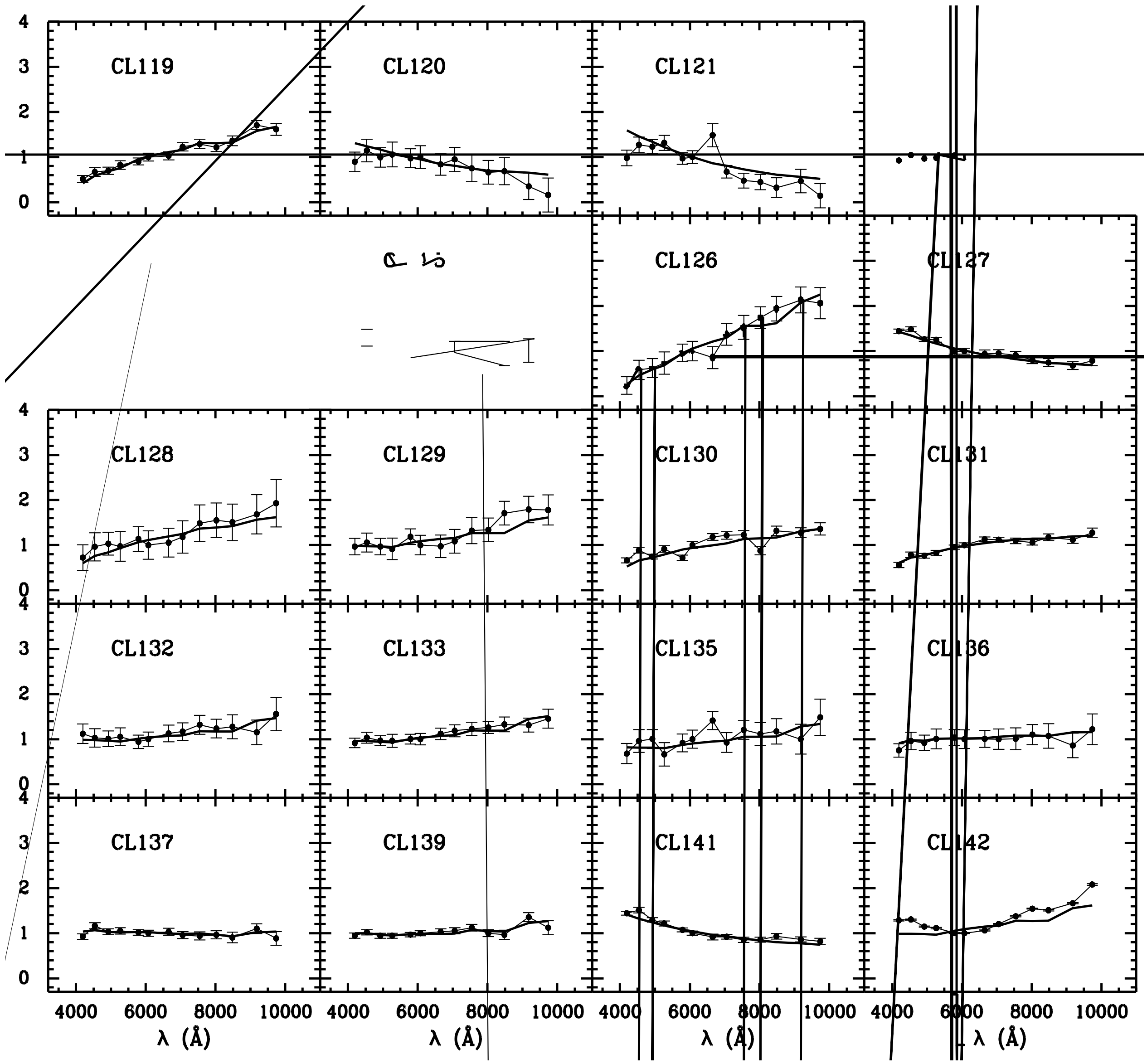



FIG. 3.—*Continued*

yr. Using the integrated *UBV* photometry and *IUE* λλ1200–3000 spectra, Ciani, D'Odorico, & Benvenuti (1984) studied the minuscule "bulge" population of M33 and found that a multigeneration model, where a young component (age of $\sim 10^7$ yr) and an old, metal-poor one (age of $\sim 5 \times 10^9$ 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.

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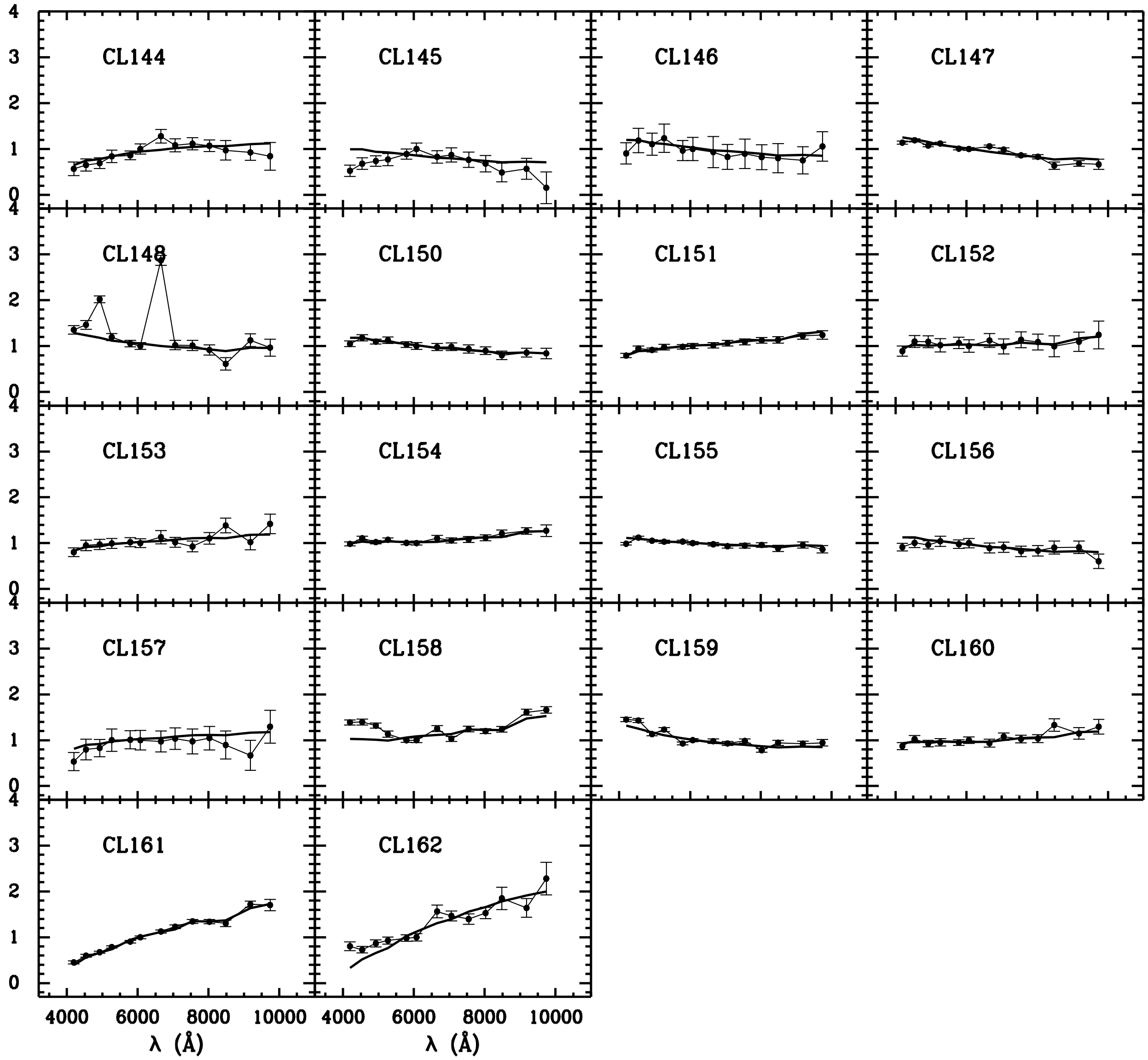


FIG. 3.—*Continued*

TABLE 4

AGE DISTRIBUTION OF 78 STAR CLUSTERS

| No. | Metallicity ($Z$) | Age (log yr) | No. | Metallicity ($Z$) | Age (log yr) |
|---|---|---|---|---|---|
| 62 .......... | 0.00040 | 9.279 | 118 ......... | 0.02000 | 9.155 |
| 64 .......... | 0.00400 | 8.806 | 119 ......... | 0.02000 | 9.155 |
| 67 .......... | 0.00400 | 7.720 | 120 ......... | 0.00400 | 6.600 |
| 68 .......... | 0.00400 | 7.021 | 121 ......... | 0.02000 | 6.620 |
| 69 .......... | 0.00040 | 9.760 | 122 ......... | 0.00400 | 8.307 |
| 71 .......... | 0.02000 | 8.606 | 124 ......... | 0.02000 | 6.860 |
| 72 .......... | 0.02000 | 9.107 | 125 ......... | 0.00400 | 6.860 |
| 73 .......... | 0.02000 | 9.107 | 126 ......... | 0.02000 | 9.954 |
| 74 .......... | 0.00400 | 9.322 | 127 ......... | 0.00040 | 7.220 |
| 75 .......... | 0.00040 | 8.757 | 128 ......... | 0.00400 | 9.107 |
| 76 .......... | 0.00400 | 8.757 | 129 ......... | 0.02000 | 6.940 |
| 77 .......... | 0.02000 | 9.009 | 130 ......... | 0.00400 | 9.057 |
| 78 .......... | 0.02000 | 6.800 | 131 ......... | 0.00040 | 9.301 |
| 79 .......... | 0.02000 | 9.107 | 132 ......... | 0.02000 | 6.980 |
| 83 .......... | 0.02000 | 6.940 | 133 ......... | 0.02000 | 6.960 |
| 84 .......... | 0.02000 | 6.860 | 135 ......... | 0.02000 | 6.940 |
| 86 .......... | 0.00040 | 9.155 | 136 ......... | 0.00040 | 8.806 |
| 87 .......... | 0.00040 | 10.061 | 137 ......... | 0.02000 | 8.057 |
| 88 .......... | 0.00400 | 6.480 | 139 ......... | 0.02000 | 7.179 |
| 89 .......... | 0.00040 | 6.580 | 141 ......... | 0.00040 | 6.660 |
| 91 .......... | 0.00040 | 9.255 | 142 ......... | 0.02000 | 6.940 |
| 92 .......... | 0.00400 | 7.699 | 144 ......... | 0.00040 | 9.107 |
| 93 .......... | 0.00400 | 6.600 | 145 ......... | 0.00040 | 8.009 |
| 94 .......... | 0.00040 | 8.356 | 146 ......... | 0.00040 | 8.009 |
| 95 .......... | 0.02000 | 6.940 | 147 ......... | 0.02000 | 6.760 |
| 96 .......... | 0.02000 | 6.920 | 148 ......... | 0.02000 | 6.840 |
| 97 .......... | 0.00400 | 10.279 | 150 ......... | 0.00040 | 8.009 |
| 99 .......... | 0.02000 | 9.107 | 151 ......... | 0.00400 | 8.757 |
| 100 ........ | 0.02000 | 6.680 | 152 ......... | 0.00400 | 8.356 |
| 101 ........ | 0.02000 | 8.057 | 153 ......... | 0.00040 | 8.906 |
| 103 ........ | 0.00400 | 6.620 | 154 ......... | 0.00040 | 8.507 |
| 107 ........ | 0.00400 | 8.857 | 155 ......... | 0.00400 | 6.960 |
| 108 ........ | 0.00400 | 8.507 | 156 ......... | 0.00040 | 8.009 |
| 109 ........ | 0.00040 | 8.657 | 157 ......... | 0.00040 | 8.957 |
| 110 ........ | 0.00040 | 8.957 | 158 ......... | 0.02000 | 6.980 |
| 112 ........ | 0.00040 | 9.207 | 159 ......... | 0.00400 | 7.179 |
| 113 ........ | 0.00040 | 7.806 | 160 ......... | 0.00040 | 8.507 |
| 115 ........ | 0.02000 | 6.840 | 161 ......... | 0.02000 | 9.225 |
| 117 ........ | 0.00400 | 8.009 | 162 ......... | 0.00400 | 10.283 |

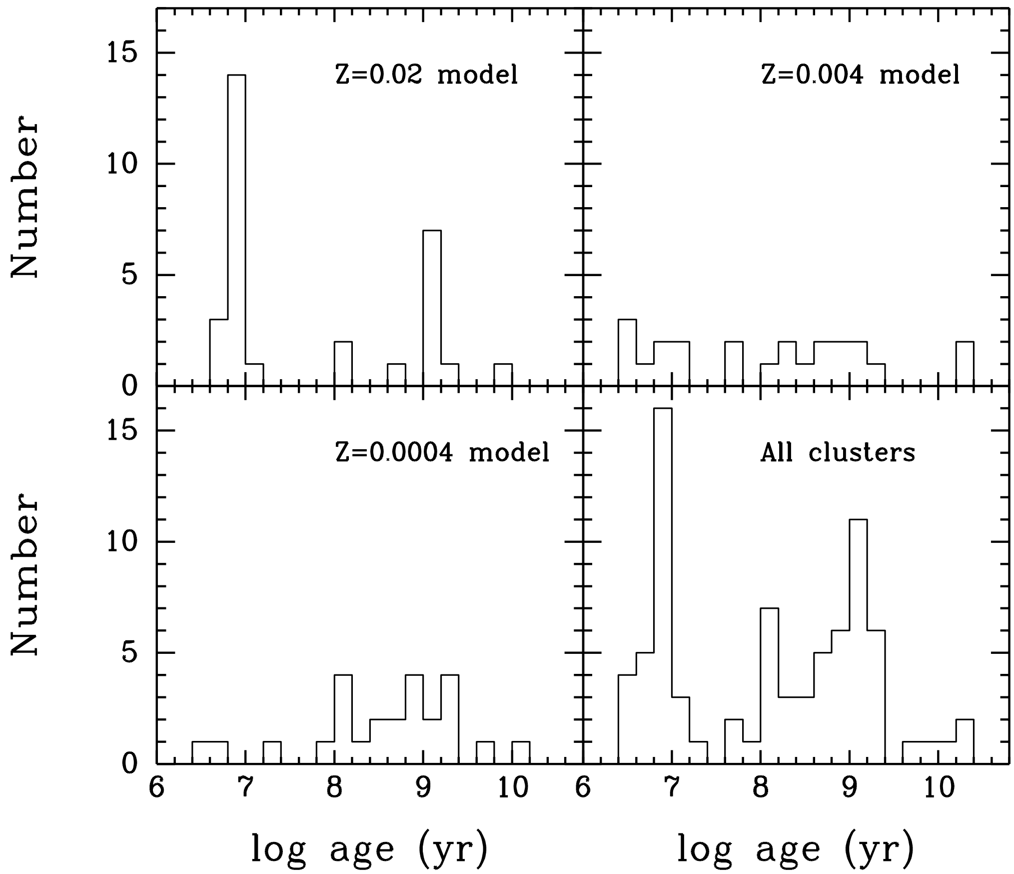


FIG. 4.—Histogram of M33 cluster ages

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