

Thirteen-Color Photometry of Open Cluster M48

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ABSTRACT. This paper presents 13 color CCD intermediate-band spectrophotometry of a field centered on the open cluster M48 (NGC 2548) from 400 to nearly 1000 nm, taken with Beijing-Arizona-Taiwan-Connecticut (BATC) Color Survey photometric system. The fundamental parameters of this cluster are derived with a new method that is based on a comparison of the spectral energy distributions (SEDs) of cluster stars and the theoretical SEDs of Padova models. We find that the best-fitting age of M48 is 0.32 Gyr, with a distance of 780 pc, a reddening of $E(B - V) = 0.04$, and a solar metallicity of $Z = 0.019$.

1. INTRODUCTION

Open clusters have long been recognized as important tools in the study of the Galactic disk. Their value lies in the improvement in accuracy for distance determination, metal content, reddening, and age produced by the collective stellar sample that shares these properties. Open clusters are therefore excellent tracers of the abundance gradient along the Galactic disk, in addition to many other important disk properties, such as the age-metallicity relation, abundance gradient evolution, disk age, and so on (Friel 1995; Twarog et al. 1997; Chen et al. 2003).

The open cluster M48, also known as NGC 2548, is quite a conspicuous object and is visible to the naked eye under good weather conditions. It was first studied by Pesch (1961), who compiled *UBV* photoelectric photometry of 37 stars and determined the cluster to have a reddening of $E(B - V) = 0.04 \pm 0.05$ and a distance of 630 pc. DDO photoelectric photometry of five red giants was obtained by Clariá (1985). From four of these red giants, he concluded that this cluster has a metallicity of $[\text{Fe}/\text{H}] = 0.1$, $E(B - V) = 0.06 \pm 0.02$, and a distance of 530 pc. Mermilliod (1981) derived an age of 0.30 Gyr, based on a synthetic composite color-magnitude diagram. Wu et al. (2002) determined absolute proper motions and membership probabilities for 501 stars in the field of M48. More recently, Rider et al. (2004) obtained a new result for M48 taken with the *u'g'r'i'z'* Sloan Digital Sky Survey (SDSS) filter system. They find that a distance of 700 pc, an age of 0.40 Gyr, and a metallicity of $[\text{Fe}/\text{H}] = 0.0$ best fit their data.

In this paper we present a new photometric result for M48 taken with BATC Color Survey photometric system. The BATC filter system consists of 15 filters with bandwidths of 150–350 Å that cover the wavelength range 3300–10000 Å, which avoids strong and variable sky emission lines (Fan et al. 1996). As the first object in BATC survey, the old open cluster M67 has been studied using color-magnitude diagrams

(CMDs; Fan et al. 1996). Using the BATC filter system, Chen et al. (2000) studied the globular cluster NGC 288 by comparing spectral energy distributions (SEDs) of bright stars with Kurucz models. The estimated effective temperatures and average value of $[\text{Fe}/\text{H}]$ for these stars are consistent with spectroscopic determinations. Based on the BATC survey observations, the main aim of this study is to simultaneously determine the fundamental parameters of M48 (such as age, distance, metallicity, and reddening) by comparing observational SEDs of cluster stars with theoretical stellar evolutionary models.

The observations and reduction of the M48 data are described in § 2. In § 3 we derive fundamental parameters of M48. Conclusions and the summary are presented in § 4.

2. OBSERVATION AND DATA REDUCTION

2.1. Observation

Our observations were conducted with the BATC photometric system at the Xinglong Station of the National Astronomical Observatories, Chinese Academy of Sciences (NAOC). The 60/90 cm f/3 Schmidt telescope was used, with a Ford Aerospace 2048 × 2048 CCD camera at its main focus. The field of view of the CCD is 58' × 58', with a plate scale of 1"7 pixel⁻¹.

The filter system of the BATC project is defined by 15 intermediate-band filters that are specifically designed to avoid most of the known bright and variable night-sky emission lines. The definition of magnitude for the BATC survey is in the AB_v system, which is a monochromatic flux system first introduced by Oke & Gunn (1983):

$$m_{\text{BATC}} = -2.5 \log F_v - 48.60, \quad (1)$$

where F_v is the appropriately averaged monochromatic flux (measured in unit of ergs s⁻¹ cm⁻² Hz⁻¹) at the effective wave-

length of the specific passband (Fukugita et al. 1996). In the BATC system, the F_ν is defined as (Yan et al. 2000)

$$F_\nu = \frac{\int d(\log \nu) f_\nu R_\nu}{\int d(\log \nu) R_\nu}, \quad (2)$$

which directly ties the magnitude to input flux. The system response (R_ν) actually used to relate the SED of the source f_ν and F_ν includes only the filter transmissions. Other effects, such as the quantum efficiency of the CCD, the response of the telescope's optics, the transmission of atmosphere, etc., are ignored. This makes the BATC system filter-defined, and the effective wavelengths are affected only at the $\pm 6 \text{ \AA}$ level after taking CCD quantum efficiency and aluminum reflection into account (Yan et al. 2000).

The flux calibration of the BATC photometric system is defined by the four spectrophotometric standard stars of Oke & Gunn (1983): HD 19445, HD 84937, BD +26°2606, and BD +17°4708. The fluxes of the four stars have been recalibrated by Fukugita et al. (1996). Their magnitudes in the BATC system have been slightly corrected recently by cross-checking with data obtained on a number of photometric nights (Zhou et al. 2001).

In the nights judged photometric by the observers, the standard stars were observed between air masses of 1.0 and 2.0 for each filter band. The observing procedure of the survey program field and photometry are described in detail in Zhou et al. (2001) and Yan et al. (2000).

Because of the very low quantum efficiency of the thick CCD used in the bluest filters, two BATC filters (a and b) are not used in the observation of the M48 field. In Table 1, for each BATC filter, we list the corresponding effective wavelength, FWHM, and exposure time.

2.2. Data Reduction

Preliminary reductions of the CCD frames, including bias subtraction and flat fielding, were carried out with an automatic data reduction procedure called PIPELINE I, which has been developed as a standard for the BATC survey in NAOC (Fan et al. 1996). The astrometric plate solution is obtained by knowing a priori the approximate plate center position and then using this information to register the brighter stars in each frame with the Guide Star Catalog (GSC) coordinate system (Jenknier et al. 1990).

A PIPELINE II program based on the DAOPHOT II stellar photometric reduction package of Stetson (1987) was used to measure the instrumental magnitudes of point sources in BATC CCD frames. The PIPELINE II reduction procedure was performed on each single CCD frame to get the point-spread function (PSF) magnitude of each point source. The instrumental magnitudes were then calibrated to the BATC standard system (Zhou et al. 2003). The average calibration error of each filter is less than 0.02 mag. The other sources of photometric error,

TABLE 1
PARAMETERS OF 13 BATC FILTERS AND THE STATISTICS
OF OBSERVATIONS

Number	Filter	λ_{eff} (\AA)	FWHM (\AA)	Exposure Time (minutes)
1	c	4180.0	310.0	38
2	d	4532.0	330.0	183
3	e	4916.0	370.0	98
4	f	5258.0	340.0	84
5	g	5785.0	290.0	64
6	h	6069.0	310.0	41
7	i	6646.0	490.0	44
8	j	7055.0	240.0	11
9	k	7545.0	190.0	21
10	m	8020.0	260.0	76
11	n	8483.0	170.0	88
12	o	9180.0	250.0	148
13	p	9736.0	280.0	134

including photon star and sky statistics, readout noise, random and systematic errors from bias subtraction and flat fielding, and the PSF fitting, are all considered in PIPELINE II, and the total estimated errors of each star are given in the final catalog (Zhou et al. 2003). Stars that are detected in at least three filters are included in the final catalog.

3. FUNDAMENTAL PARAMETERS DERIVED FROM SEDS

The CMD is the main tool used to derive the fundamental parameters of the star cluster. In the BATC photometric system, 15 filters can be used to form various CMDs. However, it is difficult to derive a consistent result from various different CMDs. On the other hand, the large number of bands available in our data set provides a sort of *low-resolution spectroscopy* that defines the SED of each star quite well. So it is possible to derive the fundamental parameters of a star cluster by fitting the SEDs of member stars with theoretical stellar evolutionary models.

3.1. Fitting Procedure and Results

The observed SED of a star is determined by intrinsic (mass, age, and metallicity) and extrinsic (distance and reddening) parameters. The member stars in a star clusters share the same age, metallicity, reddening, and distance. The aim of our new method is to compare the observed SEDs of member stars with theoretical models to obtain a combination of best-fitting cluster parameters.

Our fitting procedure can be separated into two steps. First, we calculate the deviation between observed and theoretical SEDs of each member star using different sets of cluster pa-

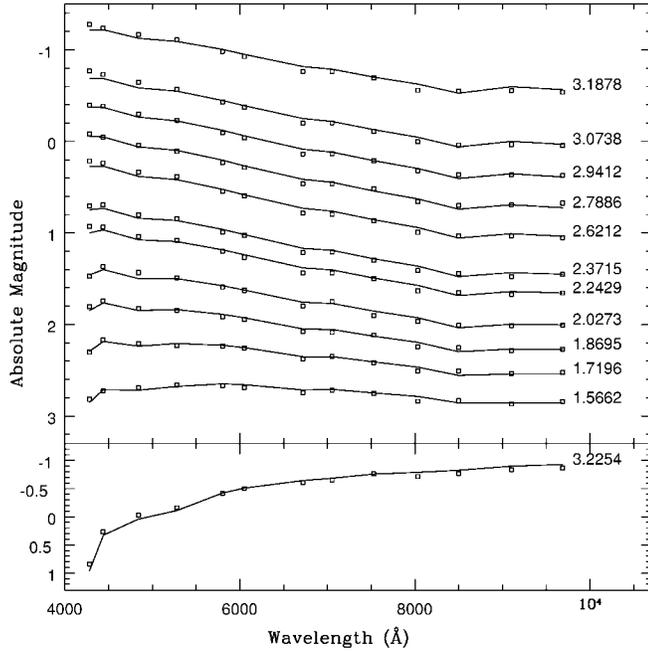


FIG. 1.—SEDs of M48 members of BATC data compared with the Padova models. Open squares indicate the observations plotted at the effective wavelengths of the BATC filters. The line represents the best-fitting theoretical SED from Girardi et al. (2000). For each line, the corresponding mass is labeled on the right in units of solar mass (M_{\odot}).

rameters, including age, metallicity, distance, and reddening:

$$m_x[E(B - V), r] = m_{x_{\text{obs}}} + 5 - 5 \log r - R_x \times E(B - V), \quad (3)$$

where $m_{x_{\text{obs}}}$ is the observed magnitude of a cluster member in filter x , $m_x[E(B - V), r]$ is the absolute magnitude corrected by distance r and reddening $E(B - V)$, R_x is an extinction coefficient that transforms the $E(B - V)$ to the BATC filter system and is derived by Chen (2000), based on the procedure in Appendix B of Schlegel et al. (1998).

The fitting criteria for a cluster member s between an observed SED and a theoretical model are defined by

$$\zeta_s[\log(t), Z, m, r, E(B - V)] = \sqrt{\frac{\sum \{m_x[E(B - V), r] - M_x\}^2}{n}}, \quad (4)$$

where M_x is the theoretical magnitude of a star in filter x , computed from a chosen theoretical isochrone model with age $\log(t)$, metallicity Z , and mass m , and n is the number of filters used in the fit.

For any set of cluster parameter combinations, we can find the smallest value of ζ_s with $\min \{\zeta_s[\log(t), Z, r, E(B - V)]\}$

for the member star s and give the best matched theoretical mass of that star. We can then get the total deviation of all member stars of a cluster using this set of fundamental parameters:

$$\zeta[\log(t), Z, r, E(B - V)] = \frac{\sum \min \{\zeta_s[\log(t), Z, r, E(B - V)]\}}{N}, \quad (5)$$

where N is the number of cluster members used in the fit. A set of fundamental parameters that best match the observed and theoretical SEDs of cluster members will yield the minimum of ζ .

At our request, L. Girardi has kindly calculated isochrones of our filter system using the known BATC filter transmission curves and the Padova stellar evolutionary models (Girardi et al. 2000, 2002). The Padova isochrone sets are computed with updated opacities and equations of state and a moderate amount of convective overshoot.

The results of a proper motion and membership study of M48 by Wu et al. (2002) are used to determine members in this cluster. Stars with membership probabilities greater than 0.7 are considered to be members (Wu et al. 2002). All stars considered as members based on their proper motions were used in our fitting.

In our fitting procedure, we chose distances from 600 to 900 pc in intervals of 10 pc, and $E(B - V)$ from 0.00 to 0.10 in intervals of 0.01. Theoretical isochrone models with metallicities of $Z = 0.08, 0.019, \text{ and } 0.030$ and ages $\log(t) = 8.0\text{--}9.0$ in intervals of 0.05 were chosen.

We find that with a distance of 780 pc and reddening $E(B - V) = 0.04$, the theoretical model with an age of 0.32 Gyr and metallicity $Z = 0.019$ gives the smallest value of ζ and best fits the observed SEDs. In Figure 1, we plot the best-fitting results for some member stars. The mass of each object in the Padova models is labeled to the right of each corresponding curve (in units of solar mass M_{\odot}). In the top panel of Figure 1, SEDs of 11 main-sequence (MS) stars with masses from 1.5662 to 3.1878 M_{\odot} are plotted. In the bottom panel of Figure 1, the SED of a red giant star is plotted. We can see that using the derived best-fitting parameters, the observed SEDs of both MS and red giant stars can fit the theoretical ones very well.

In Figure 2, we plot four representative CMDs from our data: $(c - p)$ versus c gives us the widest passband colors; $(c - e)$ versus c gives us the cleanest CMD; and $(f - i)$ versus f gives us the deepest CMD. All of the CMDs have a well-defined MS and MS turnoff point. All stars in the field of M48 are plotted in each diagram. Stars with known membership probabilities greater than 0.7, as determined from the proper motion study of Wu et al. (2002), are given distinct plotting symbols. In each CMD of Figure 2, parameters derived from SED-fitting are adopted. The theoretical isochrones with the

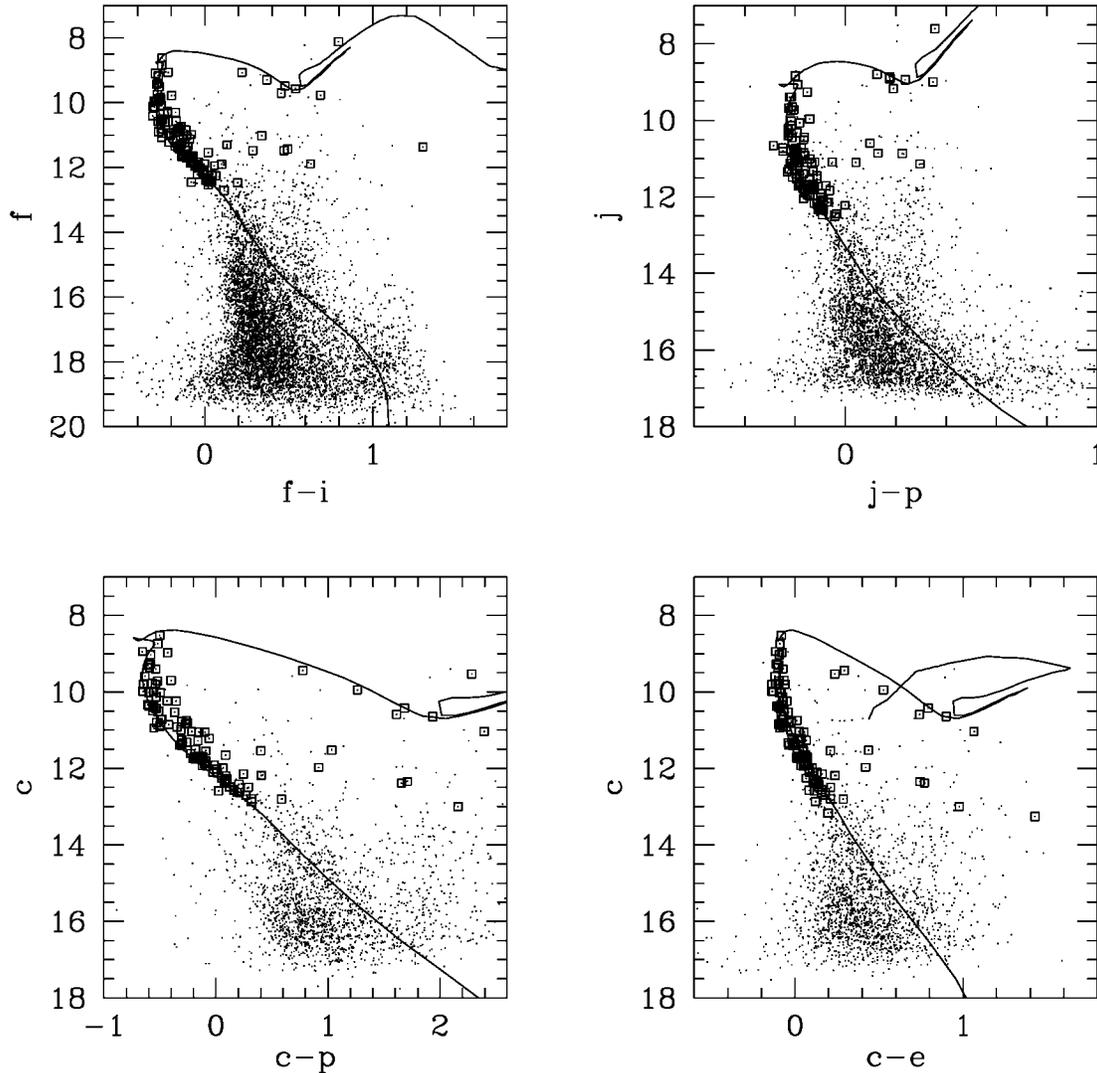


FIG. 2.—Color-magnitude diagrams for M48. Stars with membership probabilities >0.7 are considered as members (Wu et al. 2002) and are plotted as squares. A distance of 780 pc, $E(B - V) = 0.04$, and a metallicity of $Z = 0.019$ are adopted. A Padova isochrone with an age of 0.32 Gyr is overplotted in each CMD.

parameters derived by SED-fitting can fit star distributions in each CMD very well.

The uncertainties for our derived best-fitting fundamental parameters can be determined from the observational photometric errors. For each cluster member that was used in the above fitting procedure, a new magnitude in each BATC filter was generated in a Monte Carlo fashion by adding Gaussian deviates to the observed magnitude. The standard deviations of the deviates in each BATC filter were 0.05 mag, which is the maximum photometric error in most filters for sample stars used. All of these stars with new artificial magnitudes were then fitted by the same procedure as in the previous section. We repeated this simulation 100 times and identified the uncertainties caused by photometric error: distance is ± 10 pc, reddening $E(B - V)$ is ± 0.01 , and age $\log(t)$ is ± 0.05 . The

obtained metallicity keeps the same value. Therefore, the effect of photometric error on the best-fitting results is very small. At the same time, there remains the possibility of some sort of systematic calibration problem between the photometry and the models, or systematic errors in this particular set of photometry, although such errors are small (and not necessarily zero).

In Table 2 we list the fundamental parameters of M48 derived from this and previous works. The age derived in this work is consistent with those derived by previous works, the largest difference being 0.08 Gyr (Rider et al. 2004). Our derived distance is very close to the results derived in recent years (Dias et al. 2002; Rider et al. 2004). Our derived metallicity is consistent with that of Rider et al. (2004) and close to the value derived by Clariá (1985). The reddening $E(B - V)$ de-

TABLE 2
FUNDAMENTAL PARAMETERS OF M48

Author	Distance (pc)	Age (Gyr)	Reddening $E(B - V)$	Metallicity [Fe/H]
This work	780	0.32	0.04	0.0
Rider et al. (2004)	700	0.40	0.03	0.0
Dias et al. (2002)	770	0.36	0.03	0.08
Clariá (1985)	530	...	0.06	0.1
Pesch (1961)	630	...	0.04	...
Mermilliod (1981)	0.30

rived in this work is the same as that of Pesch (1961) and very close to those derived by previous works.

4. CONCLUSIONS

In this paper, we present and discuss new BATC multi-color photometry results for the intermediate-age open cluster M48. Comparing the observed SEDs of cluster member stars with the theoretical SEDs of Padova models, we find

a set of best-fitting fundamental parameters for this cluster: an age of 0.32 Gyr, a distance of 780 pc, a metallicity of $Z = 0.019$, and a reddening $E(B - V) = 0.04$. This SED-fitting result also fits CMDs formed from our data very well. Our derived values are also consistent with those of previous authors (Mermilliod 1981; Rider et al. 2004). Therefore, we can say that using the Padova theoretical isochrones, we are able to effectively fit our data obtained using the BATC filter system with theoretical isochrones and SEDs to extract useful cluster information.

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