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Membership Determination of Open Cluster M48 Based on BATC 13-Band Photometry

ZHEN-YU WU, XU ZHOU, JUN MA, ZHAO-JI JIANG, AND JIAN-SHENG CHEN

National Astronomical Observatories, Chinese Academy of Sciences, 20A Datun Road, Beijing 100012, China; zywu@bac.pku.edu.cn

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ABSTRACT. Beijing-Arizona-Taiwan-Connecticut (BATC) multiband photometric data in the field of open cluster M48 are used to determine its membership. By comparing observed spectral energy distributions of M48 stars with theoretical ones, membership probabilities of 750 stars with limiting magnitudes of 15.0 in the BATC *c* band ($\lambda_{\rm eff} = 4194$ Å) are determined. We find 323 stars with membership probabilities higher than 30% that are considered to be candidate members of M48. Comparing membership probabilities of 229 stars obtained in common between the present method and proper-motion–based methods, an 80% agreement among these methods is obtained.

Online material: extended tables

1. INTRODUCTION

Open clusters (OCs) have long been recognized as important tools in the study of the Galactic disk. They have been used to determine spiral arm structure, map the rotational curve of the Galaxy, investigate the mechanisms of star formation, constrain the initial luminosity and mass functions, and define disk abundance gradients and the age-metallicity relationship (Friel 1995; Friel et al. 2002; Chen et al. 2003; Salaris et al. 2004; von Hippel 2006; Bonatto et al. 2006).

The first step to determine the physical parameters of an open cluster is to select probable members in the vicinity of the cluster. Omitting the parameter of position, which provides us with the first clue as to the existence or nonexistence of a cluster, there are two types of independent methods to establish cluster membership: photometric and kinematic (Cabrera-Caño & Alfaro 1990).

When kinematic data are available, it is recognized that the membership probabilities obtained from the analysis of proper motions or radial velocities are more reliable. Unfortunately, few clusters have a large, homogeneous set of radial velocity data to permit a detailed analysis of the entire cluster. It is well known that proper-motion analysis is at present the most valuable criterion for establishing membership probabilities in OCs (Slovak 1977; Cabrera-Caño & Alfaro 1985).

The first attempt to statistically determine membership in an open cluster based on proper-motion data was made by Vasilevskis et al. (1958). They point out that the cluster and field probability density functions can be modeled as bivariate Gaussian distributions: a circular, normal distribution for the cluster population, and an elliptical, normal distribution for the field population. A maximum likelihood principle was developed to obtain the distribution parameters of clusters and the membership probabilities of individual stars (Sanders 1971). The parametric Vasilevskis-Sanders method has frequently been used to derive the membership in star clusters (Wu et al. 2002a; Wu et al. 2002b). However, the hypotheses for cluster and field-star distributions in the parametric Vasilevskis-Sanders method are not always true. Even if the hypotheses are realistic for some clusters, the parametric method will fail when the ratio of cluster members to field stars is small (Cabrera-Caño & Alfaro 1990). This method does not work in the case of significant internal motion in a cluster or its rotation (Slovak 1977; Javakhishvili et al. 2006).

In order to overcome some difficulties that arise from the parametric Vasilevskis-Sanders method, Cabrera-Caño & Alfaro (1990) developed a nonparametric approach to the membership problem. The key to their method is to perform an empirical determination of the probability density functions, without relying on any previous assumption about their profiles (Galadí-Enríquez et al. 1998). The nonparametric method has been used in recent years to determine membership in several OCs (Galadí-Enríquez et al. 1998; Balaguer-Núñez et al. 2004, 2005). More recently, Javakhishvili et al. (2006) presented a new method that enlarges the statistical distance between the cluster members and field stars by revealing the group of stars with the lowest relative velocities, without making any assumptions about the distribution of field stars.

Although proper-motion–based methods have been considered to be the most reliable for cluster–field segregation, these methods require high-precision proper-motion data. Several decades, or even more than 100 years, are needed to obtain these high-precision proper-motion data. Therefore, membership determination based on proper motions is very time-consuming. Furthermore, since most proper motions of stars are derived

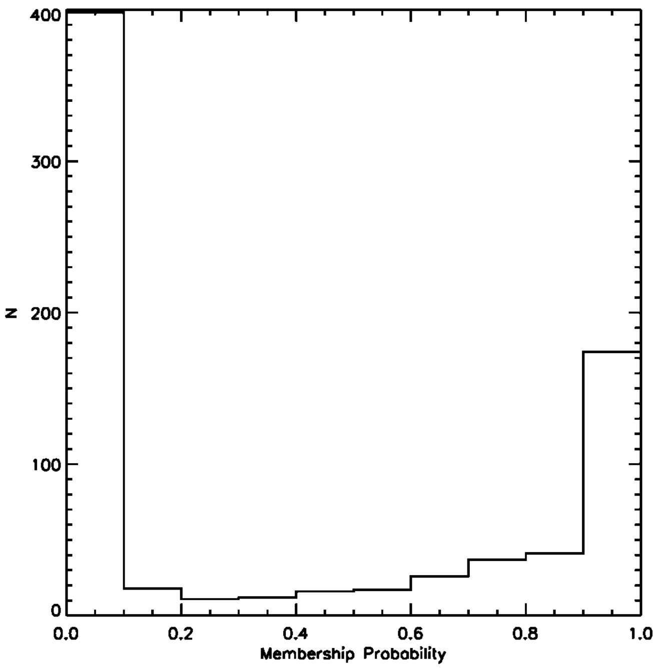

FIG. 1.—Histogram of cluster membership probability of M48. The present SED method is used to derive the membership probabilities for 750 stars with limiting magnitudes of 15.0 in the BATC *c* band.

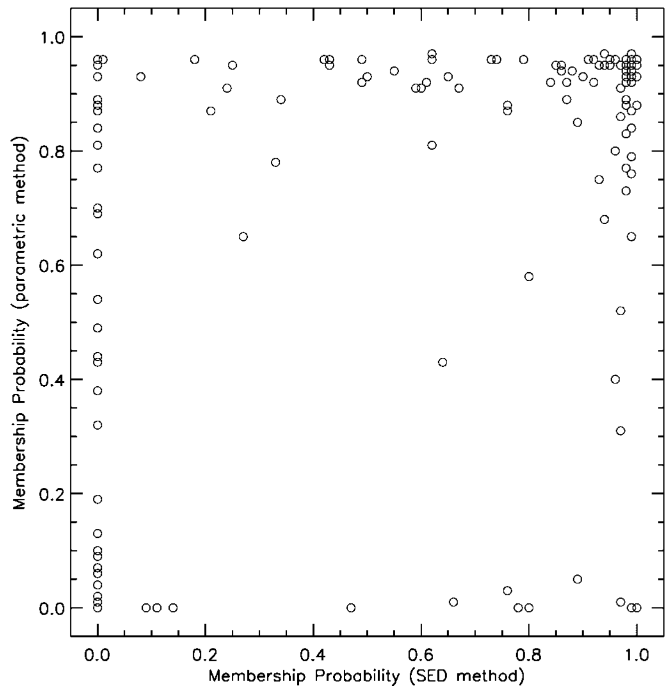

FIG. 2.—Comparison of membership probabilities for common stars determined using the SED method and the proper-motion–based parametric method.

from plate data, high-precision results can only be obtained for bright stars.

Color-magnitude diagrams (CMDs) and color-color diagrams are used to derive the fundamental parameters of clusters, and they are generally also used to determine the membership in a cluster. If a cluster field and a comparison field that only includes field stars are both obtained for study, the CMD or color-color diagram of the comparison stars is subtracted from that of the cluster field, and the diagram of the resulting difference will show most members of this cluster (Meibom 2000; von Hippel et al. 2002). However, this method obviously requires that the foreground and background of both the cluster and the comparison field be essentially identical, but this condition is not satisfied, due to the nonuniformity of the background (Baade 1983). On the other hand, if no comparison field is obtained, theoretical isochrones can be used to match the observed star sequence, and stars residing in the neighborhood of the best-fitting isochrone are considered to be members of this cluster. At the same time, the fundamental parameters of this cluster, such as age, metallicity, distance, and reddening, can be derived (Jeffries et al. 2001). In general, it cannot be reasonably ensured that the four fundamental physical parameters could be derived just by using observational results in two or three bands without knowing one of the parameters in advance. Thus, it is much more difficult to determine the members of a cluster based only on CMDs or color-color diagrams without knowing any physical parameters of the cluster. More recently, using *UBVRI* and *uvby*Hβ photometric data, Sarajedini et al. (1999) and Anthony-Twarog & Twarog (2000) presented a new method to distinguish cluster and field stars based only on observed star sequences in CMDs and color-color diagrams. Kalirai & Tosi (2004 and references therein) present a synthetic CMD method to derive the fundamental parameters of a cluster.

The Beijing-Arizona-Taiwan-Connecticut (BATC) photometric system, which includes 15 bands, provides a sort of *low-resolution spectroscopy* that defines the spectral energy distributions (SEDs) of each star. If the memberships are known with the proper-motion–based method, fitting the observed SEDs of cluster member stars with theoretical models has an advantage in that it has more observational data than the number of free parameters to be solved. Fitting the observed SEDs with theoretical ones can also be used to derive both the membership and the fundamental parameters of a cluster at the same time.

In this paper, we develop a method based on fitting SEDs of stars in a cluster field with theoretical ones to determine both the membership and the fundamental parameters of this cluster at the same time. Compared to traditional photometric membership determination methods based on CMDs or color-color diagrams, the advantage of the present method is that no comparison field is needed, and the fundamental parameters of cluster can also be derived more reliably. Moreover, this method can produce the membership probabilities of stars. Comparing proper-motion–based methods, the observational data used by the present method can be obtained within 1 month, no assumptions about the distribution profiles of cluster and field

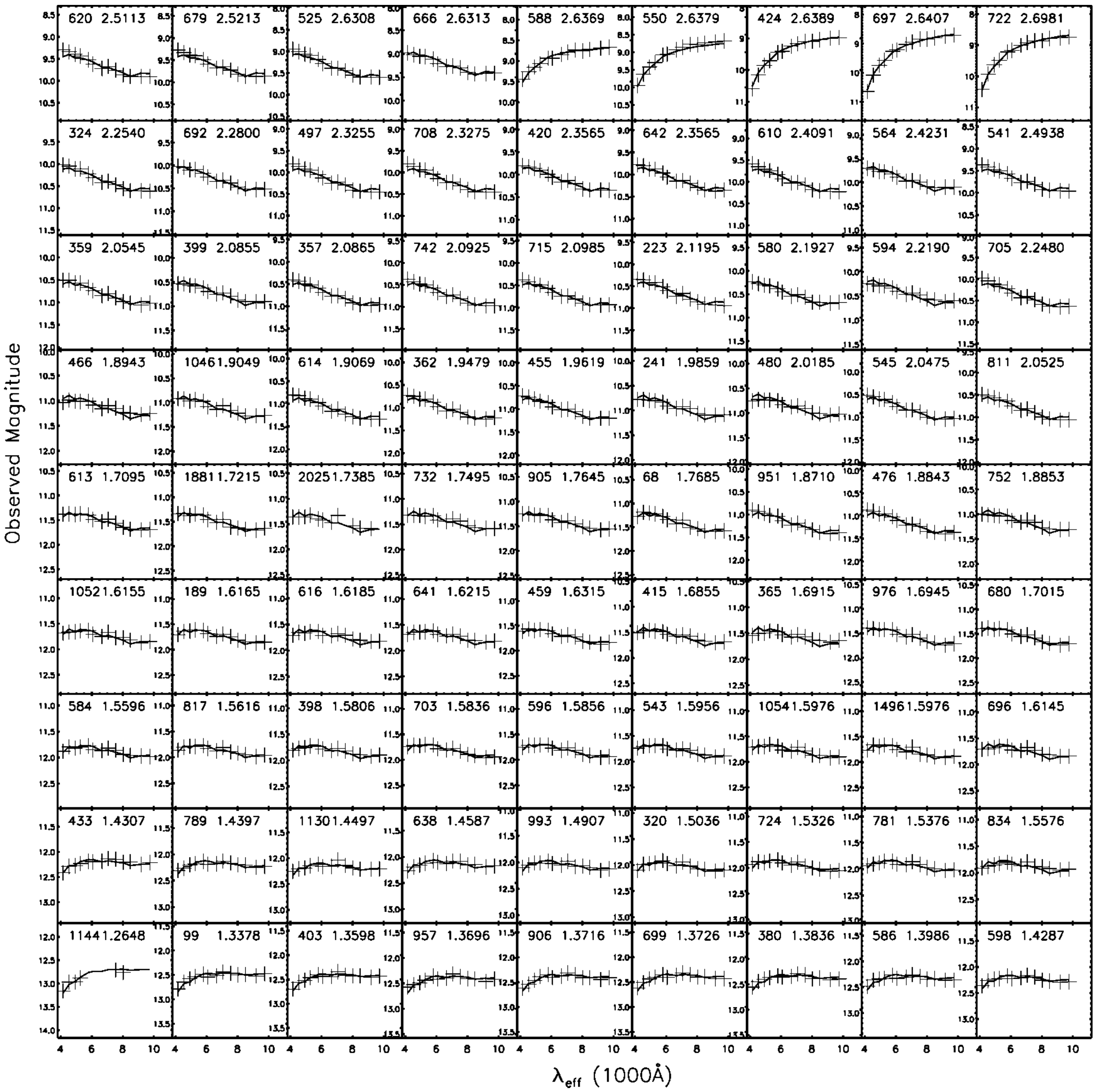

FIG. 3.—SEDs of 81 member stars of M48 determined using the present SED method and parametric and nonparametric methods based on proper-motion data. Plus signs represent the observed magnitudes in each BATC band, and the solid lines connect the best-fitting theoretical values. In each panel, IDs from Paper I and best-fitting masses for each star are also labeled.

TABLE 1
MEMBER STARS DETERMINED BY BOTH THE PRESENT SED METHOD AND THE PROPER-MOTION–BASED METHODS

No. (1)	*c* (2)	*d* (3)	*e* (4)	*f* (5)	*g* (6)	*h* (7)	*i* (8)	*j* (9)	*k* (10)	*m* (11)	*n* (12)	*o* (13)	*p* (14)	P_{SED} (15)	P_W (16)	P_B (17)	ID (18)
68	11.271	11.182	11.204	11.221	11.270	11.341	11.434	11.345	11.507	11.533	11.581	11.593	11.576	0.99	0.96	0.85	284
	0.0169	0.0075	0.0324	0.0300	0.0113	0.0085	0.0188	0.0111	0.0169	0.0090	0.0099	0.0113	0.0135				
99	12.789	12.644	12.577	12.533	12.486	12.542	12.511	12.438	12.464	12.501	12.492	12.520	12.474	0.98	0.94	0.73	459
	0.0205	0.0106	0.0326	0.0300	0.0113	0.0095	0.0190	0.0116	0.0175	0.0103	0.0115	0.0114	0.0178				
189	11.705	11.639	11.633	11.609	11.623	11.682	11.737	11.694	11.743	11.812	11.846	11.872	11.852	1.00	0.95	0.85	268
	0.0181	0.0080	0.0324	0.0298	0.0114	0.0086	0.0187	0.0114	0.0166	0.0089	0.0101	0.0114	0.0141				
223	10.338	10.354	10.418	10.413	10.506	10.599	10.721	10.658	10.793	10.853	10.908	10.917	10.944	0.74	0.96	0.85	266
	0.0167	0.0076	0.0324	0.0297	0.0111	0.0082	0.0186	0.0101	0.0165	0.0087	0.0097	0.0102	0.0116				
241	10.777	10.782	10.797	10.804	10.834	10.915	10.957	10.921	10.964	11.062	11.093	11.092	11.082	0.62	0.81	0.86	265
	0.0167	0.0075	0.0323	0.0297	0.0112	0.0084	0.0186	0.0097	0.0164	0.0087	0.0095	0.0103	0.0123				

NOTE.—Table 1 is published in its entirety in the electronic edition of the *PASP*. A portion is shown here for guidance regarding its form and content.

TABLE 2
MEMBER STARS DETERMINED ONLY BY THE PRESENT SED METHOD

No. (1)	*c* (2)	*d* (3)	*e* (4)	*f* (5)	*g* (6)	*h* (7)	*i* (8)	*j* (9)	*k* (10)	*m* (11)	*n* (12)	*o* (13)	*p* (14)	P_{SED} (15)	P_W (16)	P_B (17)	ID (18)
2	14.316	13.881	13.756	13.627	13.450	13.479	13.407	13.305	13.365	13.321	13.310	13.295	13.270	0.91	0.00	0.00	0
	0.0458	0.0108	0.0345	0.0312	0.0204	0.0137	0.0212	0.0142	0.0237	0.0113	0.0124	0.0140	0.0218				
4	13.168	12.972	12.927	12.903	99.999	99.999	12.741	12.620	12.659	12.649	99.999	12.679	12.584	0.97	0.01	0.00	461
	0.0310	0.0141	0.0352	0.0313	...	...	0.0193	0.0178	0.0200	0.0124	...	0.0170	0.0306				
6	14.751	14.547	14.413	14.282	14.138	14.138	14.038	13.930	13.982	13.935	13.912	13.887	13.872	0.75	0.00	0.00	0
	0.0472	0.0108	0.0342	0.0311	0.0177	0.0124	0.0203	0.0190	0.0199	0.0139	0.0151	0.0168	0.0238				
17	14.934	14.845	14.657	14.600	14.380	14.383	14.268	14.130	14.115	14.165	14.151	14.102	14.064	0.33	0.00	0.00	0
	0.0530	0.0439	0.0409	0.0348	0.0274	0.0267	0.0230	0.0322	0.0268	0.0206	0.0270	0.0259	0.0338				
26	13.575	13.397	13.312	13.195	13.128	13.173	13.118	12.993	13.065	13.052	13.048	13.075	13.053	0.67	0.00	0.00	0
	0.0242	0.0096	0.0329	0.0301	0.0129	0.0102	0.0194	0.0137	0.0179	0.0105	0.0129	0.0133	0.0194				

NOTE.—Table 2 is published in its entirety in the electronic edition of the *PASP*. A portion is shown here for guidance regarding its form and content.

stars are needed, and membership probabilities of stars with fainter magnitudes can be obtained. We apply this method to open cluster M48 using 13 bands of BATC photometric data. Section 2 describes the proper-motion and photometric data, as well as the theoretical model used for applying the present method. The details of our method are presented in § 3. We apply our method to open cluster M48 and compare our results with those derived by proper-motion–based methods in § 4. Finally, a summary is presented in § 5.

2. DATA AND THEORETICAL MODEL

2.1. Data Used

The open cluster M48, also known as NGC 2548, is a very conspicuous object and is visible to the naked eye under good weather conditions. There are two reasons why we have chosen this cluster as the first object for applying our present method to determine a cluster's membership. First, this cluster has been observed and calibrated in 13 bands of the BATC photometric system, as reported in our previous paper, Wu et al. (2005, hereafter Paper I). The BATC photometric system consists of 15 filters with 150–350 Å bandwidths covering the wavelength range 3300–10000 Å and avoiding strong and variable sky emission lines (Fan et al. 1996). A 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

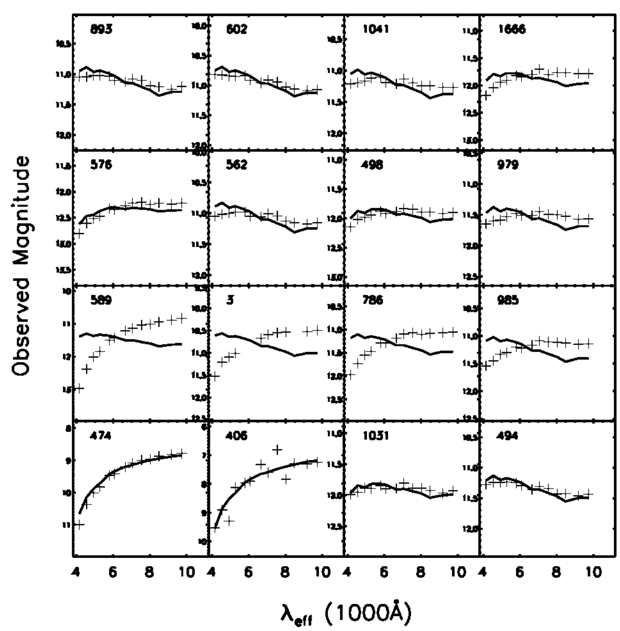

FIG. 4.—SEDs of 16 field stars determined using the present SED method but considered as member stars by parametric and nonparametric method based on proper-motion data. Symbols and line styles are the same as in Fig. 3. Only IDs from Paper I are labeled in each panel.

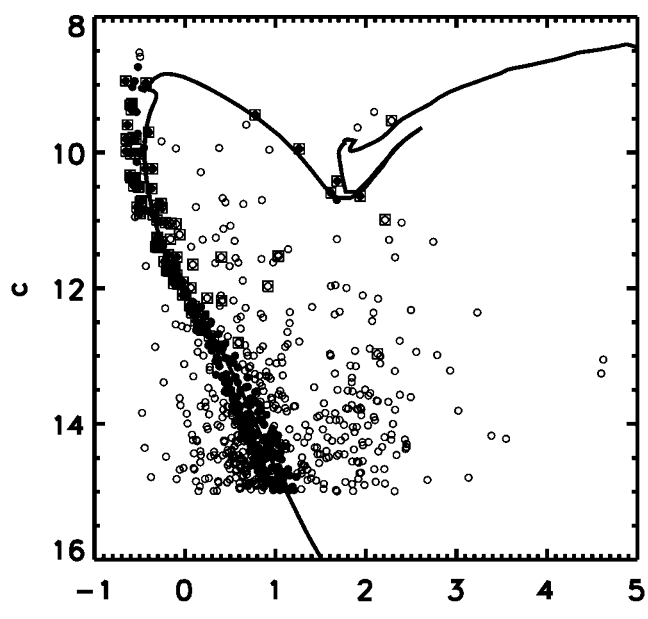

FIG. 5.—CMD of M48 with BATC *c* and *p* bands. All stars in our sample with limiting magnitudes of 15.0 in the BATC *c* band are plotted as open circles; member stars determined using present SED method are plotted as filled circles, and member stars determined based on proper motions are plotted as open squares. A distance modulus of 9.05 and reddening $E(B-V) = 0.10$ are adopted. A Padova isochrone with an age of $\log t = 8.65$ and metallicity $Z = 0.008$ is overplotted in the CMD with a solid line.

TABLE 3

Field Stars Determined by the Present SED Method but Considered as Member Stars by the Proper-Motion–based Methods

No. (1)	*c* (2)	*d* (3)	*e* (4)	*f* (5)	*g* (6)	*h* (7)	*i* (8)	*j* (9)	*k* (10)	*m* (11)	*n* (12)	*o* (13)	*p* (14)	P_{SED} (15)	P_W (16)	P_B (17)	ID (18)
3	11.528	11.210	11.090	11.013	...	...	10.674	10.595	10.547	10.534	...	10.523	10.496	0.00	0.87	0.88	293
	0.0174	0.0072	0.0328	0.0301	...	...	0.0188	0.0154	0.0167	0.0090	...	0.0096	0.0114				
406	9.529	8.903	9.292	8.120	7.964	7.894	7.324	7.601	6.810	7.837	7.285	7.293	7.245	0.00	0.88	0.84	234
	0.0164	0.0071	0.1442	0.1079	0.0120	0.0344	0.0549	0.0444	0.0615	0.0442	0.0522	0.0098	0.0103				
474	10.991	10.365	10.008	9.826	9.468	9.417	9.208	9.084	8.993	8.975	8.868	8.816	8.779	0.00	0.07	0.84	424
	0.0170	0.0071	0.0323	0.0297	0.0111	0.0084	0.0189	0.0114	0.0164	0.0085	0.0091	0.0096	0.0108				
498	12.145	12.018	11.983	11.942	11.881	11.916	11.884	11.837	11.845	11.895	11.893	11.915	11.899	0.00	0.95	0.82	212
	0.0190	0.0081	0.0325	0.0299	0.0114	0.0086	0.0187	0.0100	0.0167	0.0095	0.0104	0.0107	0.0143				
562	11.052	11.021	10.998	10.980	10.979	11.047	11.059	11.009	11.042	11.128	11.151	11.169	11.150	0.00	0.95	0.87	199
	0.0171	0.0074	0.0324	0.0297	0.0111	0.0083	0.0186	0.0103	0.0164	0.0087	0.0096	0.0099	0.0116				

Note.—Table 3 is published in its entirety in the electronic edition of the *PASP*. A portion is shown here for guidance regarding its form and content.

$58' \times 58'$, with a scale of 1.″7 pixel^{-1}. The definition of magnitude for the BATC system is in the AB$_\nu$ system, which is a monochromatic flux system introduced by Oke & Gunn (1983). The details of data reduction and the photometric results are described in Paper I.

The second reason we chose M48 is because the membership probabilities of stars in its field have been determined by Wu et al. (2002b) using the parametric Vasilevskis-Sanders method, and also by Balaguer-Núñez et al. (2005) using the nonparametric method. Proper motions of 501 stars within a 1.°6 × 1.°6 area in the region of M48 are given by Wu et al. (2002b). Ten plates of this cluster are used to derive proper motions. The oldest plate was taken in 1916, and the newest ones in 1998. The rms errors on proper motions for more than 90% of the stars are $\epsilon_{\mu_\alpha \cos\delta} = 0.92$ mas yr^{-1} and $\epsilon_{\mu_\delta} = 0.68$ mas yr^{-1}. By applying the parametric Vasilevskis-Sanders method and using a nine-parameter Gaussian model for the frequency function, Wu et al. (2002b) concluded that stars with membership probabilities higher than 70% are members. Balaguer-Núñez et al. (2005) reanalyzed the proper motion data of Wu et al. (2002b) using a nonparametric method (Galadí-Enríquez et al. 1998; Balaguer-Núñez et al. 2004) and concluded that stars with membership probabilities as high as 82% based on a nonparametric method, or with membership probabilities as high as 92% based on parametric method, are the most probable cluster members.

Therefore, we chose M48 as the first object for the appli-

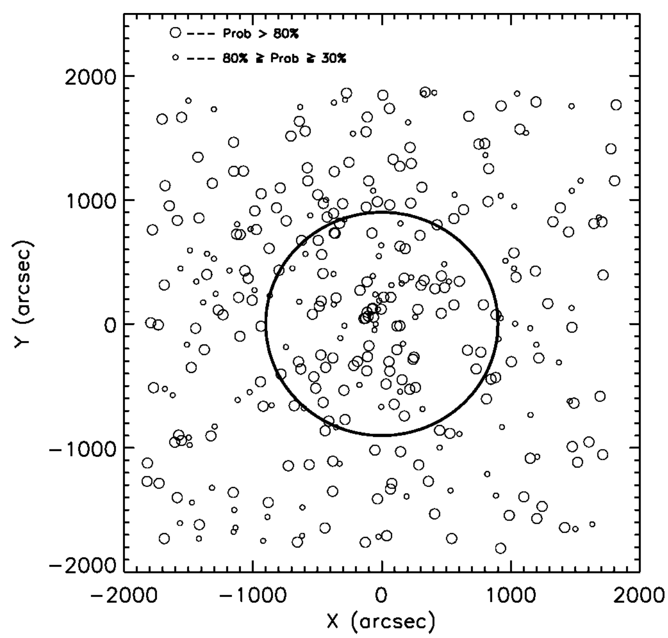

Fig. 6.—Spatial distribution of member stars determined using the present SED method. The sizes of symbols represent the different membership probabilities for each star and are labeled on the top. A circle with diameter of 30′ is also plotted.

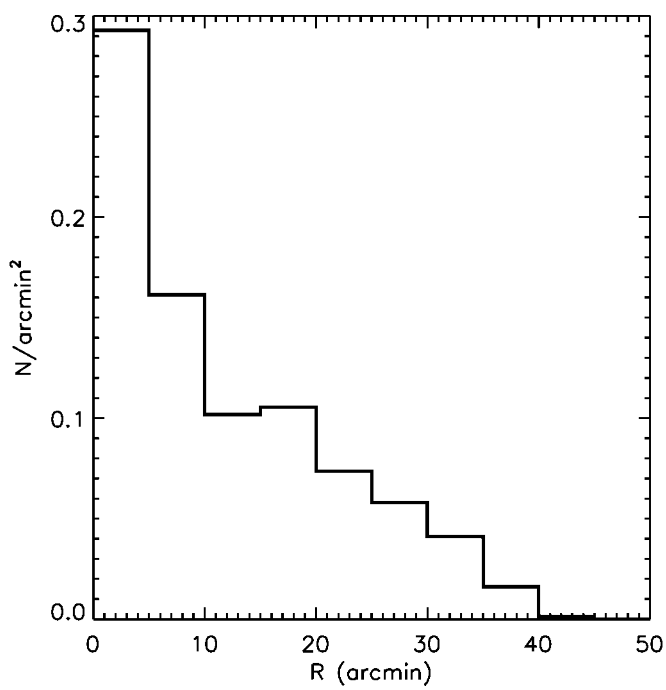

Fig. 7.—Density distribution of member stars plotted in Fig. 6.

cation of our present method based on BATC multiband photometric data, and for the comparison of our membership determinations to those derived from proper-motion data.

2.2. Theoretical Model

Padova stellar evolutionary models ("Padova 2000"; Girardi et al. 2000, 2002, and references therein) are used in our present method. Padova 2000 models present a large grid of stellar evolutionary tracks and isochrones that are suitable for modeling star clusters. The isochrones are presented for the initial chemical compositions: $Z = 0.0004$, 0.001, 0.004, 0.008, 0.019 (solar composition), 0.03, 0.04, and 0.07. These models are computed with updated opacities and equations of state, and also a moderate amount of convective overshoot. The range of initial masses goes from 0.15 to 7 $M_{\odot}$, and the evolutionary phases extend from the zero-age main sequence to either the thermally pulsing asymptotic giant branch or carbon ignition. They also present an additional set of models with solar composition, computed using the classical Schwarzschild criterion for convective boundaries.

Using the method from Girardi et al. (2002), the basic output of stellar models—the surface luminosity L and effective temperature $T_{\rm eff}$—are converted into the observable quantities (i.e., magnitudes and colors) in the BATC photometric system. Girardi et al. (2002) rewrite the formalism for converting synthetic stellar spectra into tables of bolometric corrections. The resulting formulas can be applied to any photometric system, provided that the zero points are specified by means of either ABmag, VEGAMAG, or a standard-star system. They also assemble an extended and updated library of intrinsic stellar spectra, which is mostly based on "nonovershooting" ATLAS9 models (Castelli et al. 1997) that are suitably extended to both low and high effective temperatures. This offers an excellent coverage of the parameter space of $T_{\rm eff}$, log g, and [M/H].[1]

3. METHOD

In a star field including a star cluster, the stars can be divided into many groups that share the same age, distance, metallicity, and reddening. The astronomical hypotheses in the present method can be set up such that cluster member stars are identified as those stars that have the maximum star number in the studied star field and share the same distance, age, metallicity, and reddening. In our assumption, common reddening for all member stars in a cluster is not always possible. However, the reddening maps of Schlegel et al. (1998) show very small differential reddening across the field of M48; hence, the assumption of common reddening for all member stars is reasonable.

Based on the above assumptions, the problem of membership determination of a cluster can be resolved by finding the star group that includes the maximum number of stars. In order to divide stars into different star groups according to their physical parameters (age, metallicity, distance, and reddening), theoretical stellar models with various different sets of physical parameters must be used. By fitting the observed SEDs of stars in the studied field with the theoretical model, using a given set of physical parameters, stars whose observed SEDs can be best fitted to the same theoretical ones are determined to be the members of that star group, and the physical parameters of this group are obtained from the theoretical model. This SED-fitting process is repeated for different theoretical models with different sets of physical parameters. As a result, stars in the group with the maximum number of members are considered to be the cluster members of the studied star filed.

The observed SEDs of a star are determined by parameters that are intrinsic (mass, age, and metallicity) and extrinsic (distance and reddening). In order to apply our present method, our fitting procedure is separated into two steps. First, a theoretical isochrone with different stellar masses but the same age and metallicity is chosen. A distance modulus and reddening correction are then applied to this theoretical isochrone. For the jth star, a parameter S can be defined:

$$S_j[t, Z, d, E(B-V)] = \sum_{i=1}^{n} \frac{\{m_{ij} - M_i[t, Z, d, E(B-V)]\}^2}{\sigma_{ij}^2}, \quad (1)$$

where $M_i[t, Z, d, E(B-V)]$ is the theoretical magnitude in the ith BATC band, corrected by distance modulus d and reddening $E(B-V)$ and computed from the chosen theoretical isochrone model with age t, metallicity Z, and mass m. The reddening $E(B-V)$ is transformed to each BATC band using the extinction coefficient derived by Chen (2000), based on the procedure given in Appendix B of Schlegel et al. (1998). Here m_{ij} and σ_{ij} are the observed magnitude and its error, respectively, of the jth star in the ith band, and n is the total number of observed bands for the jth star. For M_i with different stellar masses, the minimum of S_j, $S_{j,\,\rm min}$, can be obtained for the jth star using the chosen theoretical models. For a star sample, we repeated above fitting process for each star and calculate their $S_{\rm min}$ parameters. If the observed SEDs can match the theoretical SEDs, the parameter $S_{\rm min}$ should be the χ^2 distribution with $n-P$ degrees of freedom, where P is the number of free parameters to be solved. The integral probability of S_j being at least as large as $S_{j,\,\rm min}$ in the χ^2 distribution with $n-P$ degrees of freedom is taken as the membership probability of the jth star in the given cluster with the theoretical physical parametric set. If the membership probability is larger than 30%, star j is considered to be a member star for that model with the given set of physical parameters. For each set of physical parameters,

[1] The Padova stellar evolutionary models in BATC photometric system can be download at http://pleiadi.pd.astro.it/isoc_photsys.02/isoc_batc/index.html.

another parameter can be defined:

$$S_c[t, Z, d, E(B-V)] = \frac{\sum_{j=1}^{N} S_{j,\min}}{N}, \qquad (2)$$

where N is the number of member stars.

We repeated the above process for various parametric sets with different distance moduli, reddening, age, and metallicity. A parametric set with the maximum N and minimum S_c is considered to be the best-fitting set for this cluster, and the member stars in this cluster are also determined at the same time.

4. RESULTS AND DISCUSSION

We apply the present method to open cluster M48, and the parameters are chosen as follows: metallicities are taken to be $Z = 0.004$, 0.008, 0.019, 0.03, 0.04; ages $\log t$ from 8.3 to 8.8, in steps of 0.05; distance moduli from 9.0 to 9.7, in steps of 0.01; and reddening $E(B-V)$ from 0.00 to 0.15, in steps of 0.01. A total of 750 stars whose BATC c magnitude ($\lambda_{\rm eff} = 4194$ Å) is brighter than 15.0 are chosen for investigation. The limiting magnitude of 15.0 is 2 mag deeper than that used by proper-motion–based methods (Wu et al. 2002b; Balaguer-Núñez et al. 2005).

As a result, we find a best-fit set of physical parameters from the theoretical model with an age of $\log t = 8.65$, a metallicity $Z = 0.008$, a distance modulus 9.05, and $E(B-V) = 0.10$. The derived parameters are consistent with the previous determinations, within the errors (Rider et al. 2004; Paper I; Balaguer-Núñez et al. 2005). A histogram of cluster membership probability (Fig. 1) shows a clear separation between cluster members and field stars. The number of stars with membership probabilities higher than 30% is 323, and these are considered to be members of M48. The average membership probability of cluster stars is 84%, giving a contamination by field stars that is not larger than 16%.

There are 229 stars in our sample that are in common with that of Wu et al. (2002b). If we consider the most probable member stars to be those with membership probabilities higher than 82% (nonparametric method) or 92% (parametric method), as pointed out by Balaguer-Núñez et al. (2005), there are 97 stars that make up the most probable members of M48, based on proper-motion data. Among these 97 stars, 81 are considered to be members with membership probabilities higher than 30% in this paper, and another 16 are considered to be field stars. Among another 132 common stars that are considered to be field stars from the proper-motion–based method, 33 are considered to be members using the present SED method. With these limiting membership probabilities (82% for nonparametric or 92% for parametric method, and 30% for the present method), we get an 80% agreement in the segregation yielded by the present method and proper-motion–based method. It should be noted that these most probable member stars, determined with both parametric and nonparametric methods based on proper-motion data, are used for comparison. If stars with membership probabilities higher than 70% are considered as members of M48 by applying the parametric method of Wu et al. (2002b), there is an 86% agreement between the present method and the parametric method.

In Figure 2, we compare membership probabilities determined by the present method and the proper-motion–based parametric method. Although the statistical nature of the present method and the proper-motion–based methods is different, Figure 2 shows consistent results in the high membership probability region obtained by these two kinds of methods. Figure 3 shows SEDs of 81 member stars of M48 determined using both the present SED method (membership probabilities higher than 30%) and proper-motion–based methods (membership probabilities ≥92% for the parametric method, or ≥82% for the nonparametric method). Plus signs represent the observed magnitudes in each BATC band, and the solid lines connect the best-fitting theoretical values. In each panel, the ID from Paper I and the best-fitting mass for each star are labeled. It can be seen from Figure 3 that the theoretical SEDs can fit the observed SEDs very well for both giant and main-sequence stars. The changes in the SED shapes, along with the magnitudes (masses), are also clearly shown in Figure 3. Table 1 lists these 81 M48 member stars, determined using both the present SED method and the proper-motion–based methods (parametric or nonparametric method). Column (1) gives the identification number from Paper I; columns (2)–(14) are BATC magnitudes and their errors (given below each value) in 13 bands for each star; columns (15), (16), and (17) are the respective membership probabilities for each star using the present SED method, Wu et al. (2002b), and Balaguer-Núñez et al. (2005); and column (18) is the identification number in Wu et al. (2002b). Table 2 lists the M48 member stars determined using only the present SED method. The format is the same as in Table 1. If there is no identification number in Wu et al. (2002b) for a star, a “0” is given in column (18).

In Figure 4, we plot SEDs of 16 field stars that were determined using the present SED method and have membership probabilities of less than 30% but are considered as member stars by the parametric method (membership probabilities ≥92%) or the nonparametric method (membership probabilities ≥82%), based on proper-motion data. Only IDs from Paper I are labeled in each panel. For stars numbered 406, 474, 494, and 1031, the theoretical SEDs cannot be fitted to the observed SEDs, due to large deviations in some bands, although these stars are probably members. For stars numbered 3, 786, 589, and 576, the observed SEDs show that they are probably background red giants. For other stars, the theoretical SEDs cannot fit the observed ones well, and so they are probably double stars. Figure 5 plots the CMD of M48 with BATC c and p bands. All 750 stars in our sample are plotted as open circles, member stars determined using the present SED method are plotted as filled circles, and member stars determined by the proper-motion–based methods are plotted as open squares. Adopting the derived distance modulus of 9.05 and reddening $E(B-V)=0.10$, a Padova theoretical isochrone with an age of $\log t=8.65$ and metallicity $Z=0.008$ is overplotted in the CMD. From this CMD, it can be seen that most stars that are considered as members by Wu et al. (2002b) and Balaguer-Núñez et al. (2005) but considered as field stars by the present method are located in the range of the CMD where $12.5>c>10.7$ and $c-p>0.2$, and they lie at the right of the main sequence of this cluster. From the above analysis based on SEDs of those stars, most of them are probably double stars or background red giants. Table 3 lists these 16 field stars that have been determined using the present SED method but are considered as member stars from the proper-motion–based methods. The format is same as Table 1.

Figure 6 shows the spatial distribution of member stars with membership probabilities higher than 30% determined with the present method. The sizes of the symbols represent the membership probabilities of each star and are labeled at the top of the figure. A circle with diameter of $30'$ is also plotted here. Figure 6 shows that most of the member stars concentrate near the center of cluster. In Figure 7, we plot the density distribution of member stars that are plotted in Figure 6. Figure 7 shows more clearly that most of the member stars lie in the region with a radius of $10'$.

5. CONCLUSIONS

In this paper, we use BATC 13-band photometric data to develop an SED method to the determine membership and the fundamental parameters of a star cluster simultaneously. Membership probabilities of 750 stars with limiting magnitudes of 15.0 in the BATC *c* band are derived for open cluster M48, and 323 stars with membership probabilities higher than 30% are considered to be member stars of M48. Compared with the membership determinations of 229 common stars taken from parametric (Wu et al. 2002b) and nonparametric (Balaguer-Núñez et al. 2005) proper-motion–based methods, we get 80% agreement. The present SED method can investigate memberships for stars with fainter magnitudes than those found using of proper-motion–based methods (about 2 mag deeper in the case of M48), and with this method, membership probabilities of 521 stars in the field of M48 are derived for the first time. At the same time, the fundamental parameters of M48 are also derived and are found to be consistent with previous determinations (Rider et al. 2004; Paper I; Balaguer-Núñez et al. 2005).

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