**BATC 13-band Photometry of Open Cluster NGC 7789**

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**ABSTRACT**

We present 13-band CCD intermediate-band spectrophotometry of a field centered on the open cluster NGC 7789 from 400 to nearly 1000 nm, taken with Beijing-Arizona-Taiwan-Connecticut (BATC) Multi-Color Survey photometric system. By comparing observed spectral energy distributions of NGC 7789 stars with theoretical ones, the fundamental parameters of this cluster are derived: an age of $1.4 \pm 0.1$ Gyr, a distance modulus $(m - M)_0 = 11.27 \pm 0.04$, a reddening $E(B - V) = 0.28 \pm 0.02$, and a metallicity with the solar composition $Z = 0.019$. When the surface density profile for member stars with limiting magnitudes of 19.0 in the BATC $e$ band $(\lambda_{\text{eff}} = 4925 \, \text{Å})$ is fitted by King model, the core radius $R_c = 7.52'$ and the tidal radius $R_t = 28.84'$ are derived for NGC 7789. The observed mass function (MF) for main sequence stars of NGC 7789 with masses from 0.95 to 1.85 $M_\odot$ is fitted with a power-law function $\phi(m) \propto m^{\alpha}$ and the slope $\alpha = -0.96$ is derived. Strong mass segregation in NGC 7789 is reflected in the significant variation of the concentration parameters $C_0 = \log (R_t/R_c)$ for member stars of NGC 7789 within different mass ranges: $C_0 = 1.02$ for most of massive stars; $C_0 = 0.37$ for the lowest-mass MS stars. Strong mass segregation in NGC 7789 is also indicated in the significant variation of the slopes $\alpha$ in different spatial regions of the cluster: the MF for stars within the core region has $\alpha = -0.71$, much flatter than that for stars in external regions of the cluster ($\alpha = -1.20$).

*Subject headings:* open clusters and associations: individual (NGC 7789) — Stars: fundamental parameters — stars: luminosity function, mass function

1. **INTRODUCTION**

Open clusters (OCs) have long been recognized as important tools in the study of stellar formation and evolution. It is becoming increasingly clear that most stars do not form in
isolation but are instead born in relatively rich clusters. These clusters range from small associations of some tens of stars to OCs of several hundreds of stars and very rich dense OCs containing several thousands or more stars (Bonnell & Davies 1998, and references therein).

Cluster evolution is an intricate mix of dynamics, stellar evolution and external tidal influences (Portegies Zwart et al. 2001; Bergond et al. 2001). Generally speaking, mass-loss from stellar evolution is of greatest importance during the first few tens of millions of years of cluster evolution, and may well result in the disruption of the entire cluster. If the cluster survives this early phase, stellar evolutionary time-scales soon become longer than the time-scales for dynamical evolution, and two-body relaxation and tidal effects become dominant. Ultimately, these effects cause the cluster to dissociate and the stars to become part of the general field population of the Galactic disc (Portegies Zwart et al. 2001).

Energy equipartition in the cluster is the main dynamical result of tow body relaxation and leads to the lower mass stars move outwards and the higher mass stars inward, i.e., mass segregation. Numerical simulations have shown that dynamical mass segregation occurs on approximately the cluster relaxation time. In a relaxation time the cluster develops a well-defined dual regions: the core and the halo (de la Fuente Marcos 1997; Bonnell & Davies 1998). Mass segregation combined with the stripping of stars by the tidal field of the Galaxy, alters the mass function (MF) of the cluster over time to give a deficiency of low-mass stars and flattens the MF slope of the cluster (de la Fuente Marcos 1997; Kroupa 2001; Hurley et al. 2005). As the result of dynamical evolution of the cluster over time, mass segregation has been observed in many intermediate-age and old open clusters (Bonatto & Bica 2005).

The Beijing-Arizona-Taiwan-Connecticut (BATC) Multi-Color Survey photometric system consists of 15 filters of band-widths 150 — 350 Å, which cover the wavelength range 3300 — 10000 Å. This photometric system is designed to avoid strong and variable sky emission lines (Fan et al. 1996), and uses a CCD with a field of view $58\arcmin \times 58\arcmin$. The observed field size and photometric depth of BATC photometric system make it suitable for studying OCs in the Galaxy. This photometric system has been used to derive fundamental parameters and membership of the open cluster M48 (Wu et al. 2005, 2006) and to study mass segregation and MF in the old open cluster M67 (Fan et al. 1996). In this paper we will derive the fundamental parameters of the intermediate-age open cluster NGC 7789 and study the dynamical states and the MF of this cluster based on the observed data taken with the BATC photometric system.

The open cluster NGC 7789 (C 2354+564) ($\alpha_{2000} = 23^{h}57^{m}24^{s}$, $\delta_{2000} = +56^{\circ}42^{\prime}30^{\prime\prime}$; $l = 115^{\circ}532$, $b = -5^{\circ}385$) has been studied with numerous photometric and spectral ob-
servations because of its very rich stellar population (e.g., Gim et al. 1998b; Bartaštē & Tautvaišienė 2004). The first extensive $UBV$ photoelectrical and photographic photometry of this cluster was obtained by Burbidge & Sandage (1958). Their color-magnitude diagram (CMD) shows a well-defined and extended red giant branch (RGB), a prominent “clump” of core He-burning stars, numerous blue stragglers, and a main sequence (MS) whose upper end bends significantly to the red. After the study of NGC 7789 by Burbidge & Sandage (1958), individual giant stars and blue stragglers in this cluster have been used to derive the basic parameters such as reddening, distance modulus, and metallicity through various photometric ($UBV$, $uvby$, DDO, and Washington) and spectroscopic observations. The extensive CCD photometric observations have been obtained in recent years in $BV$ (Martinez Roger et al. 1994), $VI$ (Gim et al. 1998b), and $JK$ (Vallenari et al. 2000) filters, and the age of this cluster has been derived from those photometric data. In Table 1 we summarize the available fundamental parameters of NGC 7789 from literature. Table 1 shows that the derived fundamental parameters of NGC 7789 lie in a quite wide range: the reddening $E(B-V)$ from 0.22 to 0.35 with a mean of 0.28 ± 0.01; the distance modulus $(m - M)_0$ from 11.0 to 11.7 with a mean of 11.38 ± 0.05; the metallicity [Fe/H] from −0.35 to the value of solar with a mean of −0.14 ± 0.03; and the age from 1.1 Gyr to 1.7 Gyr with a mean of 1.37 ± 0.1 Gyr. McNamara & Solomon (1981) have determined relative proper motions of 1387 stars in the field of NGC 7789, 679 of which are probable members brighter than $B ≈ 15.5$. Radial velocity observations have been done by Friel et al. (2002, and references therein) and Gim et al. (1998a).

In this paper, the fundamental parameters and membership of open cluster NGC 7789 are derived with the new method based on comparison of the spectral energy distributions (SEDs) of stars with the theoretical ones (Wu et al. 2005, 2006). Using the candidate member stars determined by our photometric method, the mass segregation and MF of NGC 7789 are discussed in detail.

In the following, we describe our new observational data and photometric reduction of NGC 7789 in Section 2. In Section 3, we derive the fundamental parameters of NGC 7789. The observed MF of stars in NGC 7789 and the phenomenon of mass segregation in this cluster are discussed in Section 4. And a summary are presented in Section 5.
2. OBSERVATIONS AND DATA REDUCTION

2.1. Observations

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 scale of 1′7 pixel⁻¹. An image in the BATC e band, which was exposed 600 seconds, is presented in Figure 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 and the observing procedure of the survey program field and photometry are described in detail in Yan et al. (2000) and Zhou et al. (2001).

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 NGC 7789 field. In Table 2 for each BATC filter, we list the corresponding effective wavelength, FWHM, exposure time, and the number of frames observed.

2.2. Data Reduction and Calibration

Preliminary reductions of the CCD frames, including bias subtraction and field flattening, 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). 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 and then the aperture correction was performed to get the total instrumental magnitude for each star. 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 mean of FWHM of the PSF in each observed image is 4.39″ with 1σ error of 0.79″, which critically samples (∼ 2.5 pixels) the PSF. Therefore, the effect of undersampling on our photometric accuracy is not critical (Fan et al. 1996). For each star observed more than once in a BATC band, the final photometric result in that band is the weighted mean. Stars that are detected in at least six bands are included in the final star catalogue.
2.3. Artificial Star Test

In order to obtain the MF of NGC 7789, we estimated the completeness of our sample. Completeness corrections have been determined by artificial stars test on our data. We created 5 artificial images for each observed image by adding to the original images artificial stars. In order to avoid the creation of overcrowding, in each test we added at random positions only 15% of the original number of stars. The artificial stars had the same PSF and luminosity distribution of the original sample. The test images were reduced following the same steps and using the same parameters as on the original images. The completeness corrections for the whole image and for two different regions of the cluster, defined as the ratio of the found stars over the added artificial stars are listed in Table 3 for the BATC $e$ magnitude. In the MFs we included only the values for which the completeness corrections were 0.5 or higher for all regions in this cluster. Therefore we set the limiting magnitude to $e = 19.0$.

3. FUNDAMENTAL PARAMETERS DETERMINATION

3.1. Theoretical Model and Stars Used

The top two panels of Figure 2 show the CMDs of NGC 7789 for all observed stars around the cluster in BATC $(c - p)$ vs. $c$ and $(e - i)$ vs. $e$ bands. The bottom two panels of Figure 2 only show CMDs for stars within 8′ (the core radius, see next section) of the cluster center. It can be seen that our photometry extends from near the RGB tip to as faint as $\sim 5$ mag below the MS turnoff. The CMDs also show a prominent “clump”, and numerous blue straggler candidates. The bottom panels of Figure 2 much clearly show the MS of this cluster.

To apply our method to derive the fundamental parameters for NGC 7789, stars with BATC $e$ magnitudes less than 18.0 and within 5′ of the cluster center are chosen as our input sample. The radius of 5′ is set to discard most of contamination by field stars. The magnitude is set to eliminate the effect of large photometric uncertainties at faint magnitudes in our data. 1142 stars are included in our last sample.

Padova stellar evolutionary models (Girardi et al. 2000, 2002, and references therein; hereafter “Padova 2000”) 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. These models are computed with updated opacities and equation of state, and also a moderate amount of convective overshoot. They also present an additional set of models
with solar composition, computed using the classical Schwarzschild criterion for convective boundaries (i.e., without overshoot).\footnote{The Padova stellar evolutionary models in BATC photometric system can be downloaded at \url{http://pleiadi.pd.astro.it/isochrones.02/isoc_batc/index.html}.}

### 3.2. Method

In the present work, 13 bands data are obtained for stars in NGC 7789, which provide a sort of low-resolution spectroscopy that defines the SED for each star. Following the method presented in our previous papers \cite{Wu2005, Wu2006}, the fundamental parameters: metallicity, age, reddening and distance modulus are derived by fitting the observed SEDs of member stars in NGC 7789 with the theoretical ones of Padova 2000 models. For the $j$th star, a parameter $S$ can be defined:

$$S_j[t, Z, (m - M)_0, E(B - V)] = \sum_{i=1}^{n} \frac{(m_{ij} - M_i[t, Z, (m - M)_0, E(B - V)])^2}{\sigma_{ij}^2}$$

where $M_i[t, Z, (m - M)_0, E(B - V)]$ is the theoretical magnitude in the $i$th BATC band, corrected by distance modulus $(m - M)_0$ and reddening $E(B - V)$ and computed from the chosen theoretical isochrone model with age $t$, metallicity $Z$. The reddening $E(B - V)$ is transformed to each BATC band using the extinction coefficient derived by \cite{Chen2000}, based on the procedure given in Appendix B of \cite{Schlegel1998}. Here $m_{ij}$ and $\sigma_{ij}$ are the observed magnitude and its error, respectively, of the $j$th star in the $i$th band, and $n$ is the total number of observed bands for the $j$th star. For $M_i$ with different stellar masses, the minimum of $S_j$, $S_{j,\text{min}}$, can be obtained for the $j$th star with the chosen theoretical models. If the observed SEDs can match the theoretical SEDs, the parameter $S_{j,\text{min}}$ should be the $\chi^2$ distribution with $n - P$ degrees of freedom, where $P$ is the number of free parameters to be solved. The integral probability at least as large as $S_{j,\text{min}}$ in the $\chi^2$ distribution with $n - P$ degrees of freedom is taken as the “photometric” membership probability of the $j$th star \cite{Wu2006}. For the given stellar sample, the parameter $S_{\text{min}}$ is calculated for each star. For stars with photometric membership probabilities $P_{\text{phot}}$ greater than 10%, another parameter can be defined:

$$S_{c}[t, Z, (m - M)_0, E(B - V)] = \frac{\sum_{j=1}^{N_{\text{mem}}} S_{j,\text{min}}}{N_{\text{mem}}}$$

where $N_{\text{mem}}$ is the number of “photometric” member stars with $P_{\text{phot}}$ greater than 10%. We calculate the parameter $S_c$ for various parametric sets with different distance modulus,
reddening, age and metallicity. The parametric set with the maximum $N_{\text{mem}}$ and minimum $S_c$ is considered as the best-fitting one for this cluster (Wu et al. 2006). In order to apply the above method to NGC 7789, the parameters are chosen as follows: metallicity are taken to be $Z = 0.004, 0.008, 0.019, 0.03$; ages log $t$ from 9.0 to 9.4, in steps of 0.05; distance modulus $(m - M)_0$ from 11.1 to 11.5, in steps of 0.01; and reddening $E(B - V)$ from 0.2 to 0.4, in steps of 0.01.

3.3. RESULTS AND DISCUSSION

3.3.1. Derived Fundamental Parameters

Applying the above method, we find that with a distance modulus $(m - M)_0 = 11.27$ and a reddening $E(B - V) = 0.28$, the theoretical model with an age of log $t = 9.15$ (1.4 Gyr) and metallicity $Z = 0.019$ can best fit the observed SEDs of member stars in NGC 7789. 822 stars are determined as photometric members with $P_{\text{phot}}$ greater than 10%. In Figure 3, using the derived best-fitting parameters for NGC 7789, the theoretical isochrones are plotted in the BATC $(c - p)$ vs. $c$, $(e - i)$ vs. $e$, $(d - g)$ vs. $d$ and $(i - m)$ vs. $i$ CMDs of NGC 7789 for stars within 8′ of the cluster center. Figure 3 indicates that adopting our derived best-fitting parameters for NGC 7789, the theoretical isochrones reproduce the observed cluster’s MS, RGB fiducial and red clump stars.

Figure 4 shows the SEDs for a sample of 10 RGB and MS stars in NGC 7789 with $P_{\text{phot}}$ greater than 90%. The asterisks are for observed SEDs and the solid lines are for theoretical SEDs. Figure 4 indicates that adopting our derived best-fitting parameters for NGC 7789, the theoretical SEDs can fit the observed SEDs very well.

11 member blue stragglers of NGC 7789 that identified by Gim et al. (1998b) were included in our sample. Using our derived best-fitting parameters for NGC 7789, there are no theoretical SEDs can fit the observed SEDs of these blue stragglers. In order to find the best-fitting theoretical SEDs for these blue stragglers, we use the derived metallicity, distance modulus and reddening for this cluster and change the age of theoretical isochrones from log $t = 8.0$ to log $t = 9.4$. We find that the theoretical SEDs with an age of log $t = 8.75$ ($t = 0.56$ Gyr) can fit the observed ones of these blue stragglers. Thus, the observed SEDs of blue stragglers can be fitted by more younger stellar models than those that matched the other stars in the same cluster. The mean mass derived for these blue stragglers is 2.2 $M_\odot$, much bigger than that for the turnoff stars in the cluster ($1.8 M_\odot$).

Using our derived best-fitting parameters for NGC 7789, the membership probabilities of all observed stars are determined by comparing observed SEDs with theoretical ones and
a 10% limiting probability is set to distinguish cluster and field stars.

3.3.2. The Effects of Different Limiting Membership Probabilities and Theoretical Models

To check the effect of the chosen limiting probability for our derived parameters, we repeated the above fitting procedure with other two limiting probabilities: 50% and 1%. For the 50% limiting probability, the derived best-fitting parameters for NGC 7789 are as follows: metallicity $Z = 0.019$, age $\log t = 9.15$, reddening $E(B-V) = 0.28$, and distance modulus $(m-M)_0 = 11.30$. 728 stars are considered as member stars with the 50% limiting probability. For the 1% limiting probability, the derived best-fitting parameters are as follows: metallicity $Z = 0.019$, age $\log t = 9.10$, reddening $E(B-V) = 0.30$, and distance modulus $(m-M)_0 = 11.32$. 881 stars are considered as member stars with the 1% limiting probability. It is clear that the derived metallicity, age, reddening and distance modulus are consistent for all the adopted different limiting probabilities.

We also chose 348 stars with proper-motion-based probabilities greater than 80% and with $P_{\text{phot}}$ greater than 90% as member stars, the derived best-fitting parameters for NGC 7789 are as follows: an age $\log t = 9.15$, reddening $E(B-V) = 0.28$, $(m-M)_0 = 11.39$, and $Z = 0.019$. This result is consistent with that derived for member stars only with $P_{\text{phot}}$ greater than 10%. The internal uncertainties for our derived best-fitting parameters are as follows: $\log t = \pm 0.05$ ($t = \pm 0.1$ Gyr), $(m-M)_0 = \pm 0.04$, and reddening $E(B-V) = \pm 0.02$, which include the influence of observational errors and the estimated uncertainty inherent in our fitting method. The derived metallicity is not affected by above uncertainties, which indicates a very limited sensibility of metallicity to the variations in the limiting probabilities.

As an intermediate-age open cluster, NGC 7789 is a good object to test the stellar evolutionary models computed with or without convective overshoot. Using the Padova 2000 theoretical model computed with nonovershoot and solar composition, we derive the best-fitting parameters for NGC 7789 as follows: age $\log t = 9.05$ (1.1 Gyr), distance modulus $(m-M)_0 = 11.10$, and reddening $E(B-V) = 0.29$. In Figure 5, using the above derived fundamental parameters, we overimposed the theoretical isochrones computed with nonovershoot to the CMDs of NGC 7789 in BATC $(c-p)$ vs. $c$, $(e-i)$ vs. $e$, $(d-g)$ vs. $d$ and $(i-m)$ vs. $i$ bands. Figure 5 indicates that theoretical models computed with nonovershoot can not reproduce the observed cluster’s MS turnoff, RGB fiducial and red clump stars in CMDs of NGC 7789.
3.3.3. Comparison with Previous Studies

In this section, we compare our derived best-fitting parameters for NGC 7789 with those listed in Table 1. For metallicity, the theoretical model computed with solar composition $Z = 0.019$ match our observed data very well. This metallicity is very close to the recently derived results $\text{[Fe/H]} = -0.04$ given by Tautvaisièè̈ et al. (2005) who obtained high-resolution CCD spectroscopy of 9 RGB stars in NGC 7789, and also close to the photometric result of Twarog et al. (1997). Our result is also consistent, within the errors, with that derived by Pilachowski (1985) based on high-resolution CCD spectroscopy of 6 RGB stars in the range of quoted errors. For reddening $E(B - V)$, our derived best-fitting result of 0.28 is same as the mean listed in Table 1. For distance modulus $(m - M)_0$, our derived value of 11.27 is less than the mean of 11.38 listed in Table 1. Our derived age of 1.4 Gyr for NGC 7789 is consistent with recent results of Gim et al. (1998b) and Vallenari et al. (2000), which are both based on fitting isochrones models computed with overshoot.

590 stars in our sample have proper-motion-based membership probabilities determined by McNamara & Solomon (1981). Adopting the same limiting probability 10% for cluster-field segregation to proper-motion-based membership probabilities, we can get a 73% agreement between the present method and proper-motion-based method, which is close to the value 80% derived for open cluster M48 in our previous paper (Wu et al. 2006).

4. MASS SEGREGATION AND MASS FUNCTION

4.1. Mass Segregation

In order to study mass segregation in NGC 7789, we examine the radial surface density profile of candidate cluster members of NGC 7789. Stars within 25′ from the cluster center with limiting magnitudes of 19.0 in BATC $e$ band and $P_{\text{phot}}$ greater than 10% are chosen as preliminary members. 11 member blue stragglers identified by Gim et al. (1998b) are also included in our sample. Our candidate member stars in NGC 7789 include blue stragglers, RGB stars, subgiant branch stars, stars near the MS turnoff and MS stars extending to $\sim 19.0$ in the BATC $e$ band. The masses of stars extend from $\sim 0.8$ to $\sim 2.0M_\odot$.

To determine the radial surface density, the cluster was divided into a number of concentric rings with a step of 1.0′. The radial stellar density in each concentric circle was obtained by dividing the number of stars in each annulus by its area. To check mass segregation in NGC 7789, candidate member stars were placed in three magnitude (mass) groups based on their BATC $e$ magnitude: stars within $17.0 \leq e < 19.0$, within $15.0 \leq e < 17.0$ and within
$e < 15.0$, respectively. Figure 6 shows the radial surface density profiles for different magnitude groups. Panel a of Figure 6 shows radial surface density profile for all candidate member stars within $e < 19.0$, in the region of $21' \leq R \leq 25'$, the stellar density distribution is flat and nonzero, which indicates the contamination of field stars in our preliminary candidate member stars. For different magnitude groups, the field-star contamination corresponding to the average number of stars included in the rings located at $21' \leq R \leq 25'$ is represented in Figure 6 and indicated by dotted lines.

We fitted the empirical density law of King (1962) to our field-subtracted radial density profiles for different magnitude groups of candidate member stars in NGC 7789. The fit was performed using a nonlinear least squares fit routine which used the $1\sigma$ Poisson errors as weights. The fitted King model parameters core radius $R_c$ and tidal radius $R_t$ are labeled in each panel of Figure 6 for different magnitude groups. The fitting results are represented with solid lines. Figure 6 shows that within uncertainties the King model reproduces well the radial surface density profiles for all magnitude groups. Figure 6 indicates that evidence for mass segregation is strong when comparing King model fitting results for different magnitude groups: the group with BATC $e < 15.0$ including most massive stars such as blue straggler, RGB stars, subgiant branch stars and MS turnoff stars, has the smallest core radius and the largest tidal radius; the group with BATC $17.0 \leq e < 19.0$ including most low-mass MS stars, has the largest core radius about three times than that for high-mass stars. To represent the mass segregation more clearly, the concentration parameter $C_0 = \log (R_t/R_c)$ (King 1962) is derived for stars within different magnitude groups and listed in Table 4. The derived concentration parameters decrease from the high-mass group to the low-mass one and clearly indicate that high-mass stars are more centrally concentrated than low-mass stars.

In Table 4 we also present the radial surface density profiles for stars with $P_{\text{phot}}$ greater than 50% and 1% respectively. For different magnitude groups, the derived King model parameters are consistent within uncertainties with that derived with limiting probability of 10%. The concentration parameters are also derived and listed in Table 4. Table 4 shows that there is strong evidence for mass segregation in NGC 7789 based on surface density profiles for different magnitude (mass) groups. Adopting different limiting probabilities for photometric member stars doesn’t affect the mass segregation represented in the present data.
4.2. Mass Functions

The MF of stars can be fitted with a power-law function $\phi(m) \propto m^\alpha$ (Kroupa 2001). The present observation, which covers a large field of view of NGC 7789, provides an opportunity to study the spatial distribution of MF in this cluster. The procedure to choose preliminary candidate member stars is the same as in the previous section, but we take the MS turnoff as the bright limit ($e \sim 13.5$). The mass of each candidate member star is determined in the procedure of fitting observed SED of member star with the theoretical model, in which our derived best-fitting parameters for NGC 7789 are adopted. The final sample includes member stars with masses from $\sim 0.8$ to $\sim 1.85 M_\odot$.

After having corrected for completeness in different regions of NGC 7789, the MFs for different regions of this cluster are presented in Figure 7. The field-star contamination is estimated in the region at $21' \leq R \leq 25'$. Figure 7 shows a break of MFs followed by slope flattening for masses in the range $m \leq 0.95 M_\odot$, which is more noticeable in the central region (panel c). MF break has been observed in many intermediate-age and old open clusters. The presence of the MF break essentially reflects the effects of the internal dynamics of clusters on the MFs and/or some fundamental property of the initial mass function (IMF) associated to different conditions in star formation (Bonatto & Bica 2005). Solid lines in Figure 7 represent the fitted power-law functions for masses in the range $0.95 \leq m \leq 1.85 M_\odot$. The derived fitting parameters for MFs of NGC 7789 are listed in Table 5. Figure 7 and Table 5 indicate that the MF slopes flatten from the outskirts to the inner regions. This flat reflects the advanced dynamical state of NGC 7789, particularly the effects of mass segregation analyzed in the previous section. The overall MF slope $\alpha = -0.96$ in the mass range $0.95 \leq m \leq 1.85 M_\odot$ is much flatter than the universal IMF slope $\alpha = -2.3$ (Kroupa 2001). Martinez Roger et al. (1994) also find that the faint MS ($V < 15.0$) appears rather depopulated of stars and derive a slope of $-1.3$ for those faint MS stars. The flat overall MF slope can be accounted for by low-mass stars evaporation resulting from mass segregation and external effects such as tidal stripping by the Galactic gravitational field (Bonatto & Bica 2005). Thus we can’t get the IMF of this cluster from the present observed MF.

To check the effects for our derived MFs of NGC 7789 caused by adopting different photometric limiting probabilities for choosing candidate member stars, limiting probability 50% and 1% are used to determine candidate member stars. Table 5 lists the fitted parameters for MFs of NGC 7789 with limiting probabilities 50% and 1% respectively. Table 5 indicates that the derived MF slopes in different regions in the cluster are consistent within uncertainties for different limiting probabilities.
5. SUMMARY

In this paper, we present new BATC 13-band photometric results for the intermediate-age open cluster NGC 7789. Comparing the observed SEDs of cluster member stars with the theoretical SEDs of Padova 2000 models, we derived a set of best-fitting fundamental parameters for this cluster: an age of $\log t = 9.15 \pm 0.05$ (1.4 ± 0.1) Gyr, a distance modulus $(m - M)_0 = 11.27 \pm 0.04$, a reddening $E(B - V) = 0.28 \pm 0.02$, and a metallicity $Z = 0.019$. The theoretical SEDs fitted the observed SEDs of RGB stars and MS stars very well, but can’t reproduce the observed SEDs of blue stragglers in NGC 7789. Our derived fundamental parameters for NGC 7789 are consistent with recently derived results for this cluster (Gim et al. 1998b; Bartasūtė & Tautvaisienė 2004).

Surface density profiles for stars within different magnitude (mass) ranges are fitted by King model (King 1962) and the core radius $R_c$, tidal radius $R_t$ and the concentration parameters $C_0 = \log (R_t/R_c)$ are derived. For stars within limiting magnitudes of 19.0 in the BATC e band, we derived $R_c = 7.52'$ and $R_t = 28.84'$. The derived concentration parameters $C_0$ are significantly different for stars within different mass ranges: the $C_0$ is the minimum for stars within the highest-mass range contrast to the value for stars within the lowest-mass range. This structure parameter variation indicates strong mass segregation in NGC 7789.

MFs for MS stars with masses from 0.95 to 1.85 $M_\odot$ in different spatial regions of the cluster are fitted by a power-law function $\phi(m) \propto m^\alpha$. We derived $\alpha = -0.96$ for the whole sample of candidate member stars. The MF slopes significantly change from the central region to the outskirts: $\alpha = -0.71$ for the central region and $\alpha = -1.20$ for the outskirts. The significant variation of MF slopes in different spatial regions also indicates the presence of strong mass segregation and that NGC 7789 has undertaken strong dynamical evolution.

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Fig. 1.— The exposed 600s image in BATC e band centered on NGC 7789 with a view of field of $58' \times 58'$. 
Fig. 2.— The BATC \((c - p)\) vs. \(c\) and \((e - i)\) vs. \(e\) CMDs for NGC 7789. The top panels are for all stars observed around NGC 7789; the bottom panels are for stars within 8′ (the core radius) of the cluster center.
Fig. 3.— The BATC \((c - p)\) vs. \(c\), \((e - i)\) vs. \(e\), \((d - g)\) vs. \(d\) and \((i - m)\) vs. \(i\) CMDs of NGC 7789 for stars within 8' of the cluster center, along with the best-fitting Padova 2000 theoretical isochrones computed with a moderate amount of convective overshoot. The derived best-fitting parameters for NGC 7789 are adopted as follows: metallicity \(Z = 0.019\), age \(\log t = 9.15\), distance modulus \((m - M)_0 = 11.27\), and reddening \(E(B - V) = 0.28\).
Fig. 4.— SEDs of member stars in NGC 7789. The asterisks are for observed SEDs, the solid lines are for theoretical SEDs with our derived best-fitting parameters for this cluster: Metallicity $Z = 0.019$, age $\log t = 9.15$, distance modulus $(m - M)_0 = 11.27$, and reddening $E(B - V) = 0.28$. The identification number (ID) for each star in our star catalog is labeled in each panel.
Fig. 5.— Same as Fig. 3 but the best-fitting Padova 2000 theoretical isochrones computed with nonovershoot and the fundamental parameters for NGC 7789 are adopted as follows: Metallicity $Z = 0.019$, age $\log t = 9.05$, distance modulus $(m - M)_0 = 11.10$, and reddening $E(B - V) = 0.29$. Comparing with the result presented in Fig. 3 derived with overshoot theoretical model, the best-fitting theoretical isochrone with nonovershoot can not reproduce the observed cluster’s MS turnoff, RGB fiducial and red clump stars.
Fig. 6.— Radial surface density profile of member stars in NGC 7789 with photometric membership probabilities greater than 10%. The average background levels are shown as dotted lines and error bars present 1σ Poisson errors. The solid lines show the best-fitting King models to the radial profiles. The fitted King model parameters: core radii $R_c$ and tidal radii $R_t$ are labeled in each panel for the labeled different magnitude groups.
Fig. 7.— Field-corrected mass functions in different spatial regions of NGC 7789. Error bars represent the 1σ Poisson errors. Solid lines indicate the best-fitting power-law function \( \phi(m) \propto m^\alpha \) for stars with mass between 0.95 and 1.85 \( M_\odot \).
Table 1. Literature Estimates of Fundamental Parameters for NGC 7789

| $E(B-V)$ | $(m - M)_0$ | $[\text{Fe}/\text{H}]$ | Age (Gyr) | Method | References |
|----------|-------------|-----------------|-----------|--------|------------|
| 0.28     | 11.36 ± 0.2 | ...             | ...       | $UBV$ photoelectric and photographic photometry | 1 |
| 0.23     | 11.31       | ...             | ...       | determined from existing data$^a$ | 2 |
| 0.32 ± 0.03 | 11.0 ± 0.15 | ...             | ...       | $uvbyH_B$ photoelectric photometry, 12 blue stragglers | 3 |
| 0.26     | 11.5 ± 0.2  | −0.2 ± 0.1      | ...       | $UBV_{yz}$ photoelectric photometry, 19 red giants | 4 |
| 0.24 ± 0.01 | 11.5 ± 0.1  | Solar          | ...       | $UBV$ and DDO photoelectric photometry, 22 red giants | 5 |
| 0.22 ± 0.02 | −0.35 ± 0.07 | ...             | ...       | determined from existing data$^b$, 12 red giants | 6 |
| 0.27     | ...         | ...             | ...       | determined from existing data$^c$, 7 blue stragglers | 7 |
| 0.31 ± 0.03 | 11.34 ± 0.3$^*$ | −0.12 ± 0.10$^d$ | 1.6 ± 0.5 | $uvby$ photoelectric photometry, 28 blue stragglers | 8 |
| ...      | ...         | −0.1 ± 0.2      | ...       | high-resolution CCD spectroscopy, 6 giants | 9 |
| ...      | ...         | −0.05$^e$       | ...       | Washington photoelectric photometry, 3 red giants | 10 |
| 0.35     | 11.7        | ...             | 1.1       | determined from exiting data$^e$, isochrone-fitting | 11 |
| 0.32 ± 0.03 | 11.34 ± 0.2$^*$ | Solar          | 1.2 ± 0.3 | $BV$ CCD photometry, isochrone-fitting | 12 |
| ...      | ...         | 1.34 ± 0.18     | ...       | $\Delta V$ method$^a$ | 13 |
| 0.29$^f$ | 11.55$^*$   | −0.08 ± 0.02    | ...       | Determined from existing data$^b$ | 14 |
| 0.28     | ≤ 11.33$^*$ | −0.2 − 0.0      | 1.6 − 1.7 | $VI$ CCD photometry, ~ 1" $\times$ 1" FOV, isochrone-fitting | 15 |
| 0.30     | 11.25       | −0.25 ± 0.11    | 1.4       | IR $JK$ CCD photometry, 8" $\times$ 8" FOV, isochrone-fitting | 16 |
| ...      | ...         | −0.16           | ...       | high-resolution CCD spectroscopy, 8 blue stragglers | 17 |
| 0.27 ± 0.09 | −0.24 ± 0.09 | ...             | ...       | moderate-resolution CCD spectroscopy, 57 red giants | 18 |
| 0.25 ± 0.02 | 11.32 ± 0.03 | −0.18 ± 0.09    | ...       | Vilnius photoelectric photometry, 24 red giants | 19 |
| ...      | ...         | −0.04 ± 0.05    | ...       | high-resolution CCD spectroscopy, 9 red giants | 20 |

$^a$ $UBV$ data taken from Burbidge & Sandage (1958).

$^b$ DDO photoelectric data taken from Janes (1977).

$^c$ $uvbyH_B$ data taken from Strom & Strom (1970). $UBV$ data taken from Burbidge & Sandage (1958).

$^d$ Adopting $[\text{Fe}/\text{H}] = +0.13$ for the Hyades (Boesgaard & Friel 1990).

$^e$ *Reported as $[\text{A}/\text{H}]$ in Washington photometry system.

$^f$ Averaged result from Twarog et al. (1997).

*Inferred from the reported apparent modulus $(m - M)_V$, adopting $A_V/E(B-V) = 3.1$.

References. — (1) Burbidge & Sandage 1958; (2) Arp 1962; (3) Strom & Strom 1970; (4) Jennens & Helfer 1975; (5) Janes 1977; (6) Claría 1979; (7) Breger & Wheeler 1980; (8) Twarog & Tyson 1985; (9) Pilachowski 1985; (10) Canterna et al. 1986; (11) Mazzei & Pigatto 1988; (12) Martinez Roger et al. 1994; (13) Carraro & Chiosi 1994; (14) Twarog et al. 1997; (15) Gim et al. 1998b; (16) Vallenari et al. 2000; (17) Schönberner et al. 2001; (18) Friel et al. 2002; (19) Bartasiištė & Tautvaisienė 2004; (20) Tautvaisienė et al. 2005.
Table 2. Parameters of 13 BATC Filters and Statistics of Our Observations

| No. | Filter Name | $\lambda_{eff}$ (Å) | FWHM (Å) | Exposure (Sec) | Numbers of Images |
|-----|-------------|----------------------|----------|----------------|------------------|
| 1   | c           | 4194                 | 309      | 4200           | 5                |
| 2   | d           | 4540                 | 332      | 16500          | 16               |
| 3   | e           | 4925                 | 374      | 24721          | 22               |
| 4   | f           | 5267                 | 344      | 11400          | 11               |
| 5   | g           | 5790                 | 289      | 7500           | 7                |
| 6   | h           | 6074                 | 308      | 6300           | 6                |
| 7   | i           | 6656                 | 491      | 4080           | 5                |
| 8   | j           | 7057                 | 238      | 6300           | 6                |
| 9   | k           | 7546                 | 192      | 8280           | 9                |
| 10  | m           | 8023                 | 255      | 10200          | 10               |
| 11  | n           | 8484                 | 167      | 4200           | 5                |
| 12  | o           | 9182                 | 247      | 13200          | 14               |
| 13  | p           | 9739                 | 275      | 2400           | 5                |

Table 3. Completeness Analysis Results for NGC 7789

| $\Delta e$ | $0.0 < R < 25'$ | $0.0 < R < 10'$ | $10' \leq R < 25'$ |
|------------|-----------------|-----------------|---------------------|
| 13 - 14    | 0.99            | 0.98            | 1.00                |
| 14 - 15    | 0.96            | 0.96            | 0.97                |
| 15 - 16    | 0.94            | 0.93            | 0.95                |
| 16 - 17    | 0.91            | 0.88            | 0.93                |
| 17 - 18    | 0.86            | 0.81            | 0.88                |
| 18 - 19    | 0.74            | 0.68            | 0.75                |
| 19 - 20    | 0.43            | 0.40            | 0.44                |
Table 4. Fitted Parameters for Surface Density Profiles of NGC 7789

| Magnitude Range | \( R_c (') \) | \( R_t (') \) | \( C_0 \) | \( R_c (') \) | \( R_t (') \) | \( C_0 \) | \( R_c (') \) | \( R_t (') \) | \( C_0 \) |
|-----------------|---------------|---------------|--------|---------------|---------------|--------|---------------|---------------|--------|
| \( e < 19.0 \)  | 7.52          | 28.84         | 0.58   | 7.39          | 28.16         | 0.58   | 7.69          | 29.48         | 0.58   |
| \( e < 15.0 \)  | 3.87          | 40.80         | 1.02   | 4.32          | 27.50         | 0.80   | 4.02          | 33.65         | 0.92   |
| \( 15.0 \leq e < 17.0 \) | 8.37          | 26.63         | 0.50   | 9.19          | 22.55         | 0.39   | 9.41          | 23.69         | 0.40   |
| \( 17.0 \leq e < 19.0 \) | 11.92         | 27.87         | 0.37   | 13.61         | 26.39         | 0.29   | 11.58         | 31.15         | 0.43   |

Table 5. Fitted Parameters for Mass Functions of NGC 7789

| Distance \( R (') \) | \( \alpha \) (\( P_{\text{phot}} > 10\% \)) | \( \alpha \) (\( P_{\text{phot}} > 50\% \)) | \( \alpha \) (\( P_{\text{phot}} > 1\% \)) |
|----------------------|--------------------------------|--------------------------------|--------------------------------|
| \( 0.0 \leq R < 20.0 \) | -0.96                        | -0.90                        | -0.97                        |
| \( 0.0 \leq R < 10.0 \)  | -0.71                        | -0.65                        | -0.76                        |
| \( 10.0 \leq R < 20.0 \)  | -1.20                        | -1.21                        | -1.18                        |