Determination of Fundamental Properties of an M31 Globular Cluster from Main-Sequence Photometry

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ABSTRACT. M31 globular cluster B379 is the first extragalactic cluster whose age was determined by main-sequence photometry. In the main-sequence photometric method, the age of a cluster is obtained by fitting its color-magnitude diagram (CMD) with stellar evolutionary models. However, different stellar evolutionary models use different parameters of stellar evolution, such as range of stellar masses, different opacities and equations of state, and different recipes, and so on. So, it is interesting to check whether different stellar evolutionary models can give consistent results for the same cluster. Brown et al. constrained the age of B379 by comparing its CMD with isochrones of the 2006 VandenBerg models. Using SSP models of Bruzual & Charlot and its multiphotometry, ZMa et al. independently determined the age of B379, which is in good agreement with the determination of Brown et al. The models of Bruzual & Charlot are calculated based on the Padova evolutionary tracks. It is necessary to check whether the age of B379 as determined based on the Padova evolutionary tracks is in agreement with the determination of Brown et al. In this article, we redetermine the age of B379 using isochrones of the Padova stellar evolutionary models. In addition, the metal abundance, the distance modulus, and the reddening value for B379 are reported. The results obtained are consistent with the previous determinations, which include the age obtained by Brown et al. This article thus confirms the consistency of the age scale of B379 between the Padova isochrones and the 2006 VandenBerg isochrones; i.e., the comparison between the results of Brown et al. and Ma et al. is meaningful. The results reported in this article of values found for B379 are: metallicity $[M/H] = \log(Z/Z_\odot) = -0.325$, age $\tau = 11.0 \pm 1.5$ Gyr, reddening $E(B-V) = 0.08$, and distance modulus $(m-M)_0 = 24.44 \pm 0.10$.

Online material: color figure

1. INTRODUCTION

Globular clusters (GCs), relics of some of the earliest phases of star and galaxy formation, can be analyzed to understand how soon after the big bang the various stellar systems formed. The most direct method for determining the age of a star cluster is main-sequence photometry, in which the isochrone that minimizes the discrepancies between the observed and calculated sequences can exactly present the estimated cluster age. However, this method has only been applied to the Galactic GCs and GCs in the satellites of the Milky Way (e.g., Rich et al. 2001) prior to its use by Brown et al. (2004a) to constrain the age of an M31 GC, B379 based on the CMD extending more than 1.5 mag below the main-sequence turnoff. The CMD of B379 was constructed from the extremely deep images with the Advanced Camera for Surveys (ACS) on the Hubble Space Telescope (HST).

In general, ages of extragalactic star clusters are obtained by comparing integrated photometry with models of simple stellar populations (SSPs). For examples, Ma et al. (2001, 2002a, 2002b, 2002c) and Jiang et al. (2003) estimated ages for star clusters in M33 and M31 by comparing the SSP models of Bruzual & Charlot (1996, unpublished) with their integrated photometric measurements in the Beijing-Arizona-Taiwan-Connecticut (BATC) photometric system; de Grijs et al. (2003a) determined ages and masses of star clusters in the fossil starburst region B of M82 by comparing their observed cluster spectral energy distributions (SEDs) with the model predictions for an instantaneous burst of star formation (see also de Grijs et al. 2003b, 2003c). Bik et al. (2003) and Bastian et al. (2005) derived ages, initial masses, and extinctions of M51 star cluster candidates by fitting STARBURST99 SSP models (Leitherer et al. 1999) to their observed SEDs in six broadband and two narrowband filters from the Wide Field Planetary Camera 2 (WFPC2) onboard the HST. Ma et al. (2006a) estimated...
ages and metallicities for 33 M31 GCs by comparing between models of Bruzual & Charlot (2003, hereafter BC03) and their BATC multiband photometric data. Ma et al. (2006b) derived the age and reddening values of the M31 GC 037-B327 based on photometric and BC03 measurements in a large number of broad and intermediate bands, from the optical to the near-infrared. Fan et al. (2006) determined new ages for 91 M31 GCs from Jiang et al. (2003) based on improved photometric data and BC03 models. In particular, Ma et al. (2007) derived the age of B379\(^5\) by comparing its photometric data with BC03 models. The age obtained by Ma et al. (2007) is \(9.5^{+1.15}_{-0.99}\) Gyr, which is consistent with the determination of \(10^{+2.5}_{-1.0}\) Gyr by Brown et al. (2004a) using main-sequence photometry.

The nearest large GC system outside the Milky Way is that of the Andromeda Galaxy (=M31), which is located at a distance of 770 kpc (Freedman & Madore 1990). The first M31 GC resolved into stars was studied from the ground by Heasley et al. (1988), who only resolved the red giant branch of G1. Subsequently, some authors, such as Ajhar et al. (1996), Fusi Pecci et al. (1996), Rich et al. (1996), Holland et al. (1997), Jablonka et al. (2000), and Williams & Hodge (2001a, 2001b) have used images from the HST WFPC2 to construct the CMDs of M31 star clusters in order to determine their metallicities, reddening, and ages. However, these CMDs are not deep enough to show conspicuous main-sequence turnoffs.

Since the luminosity of the horizontal branch (HB) in stellar populations older than about 8 Gyr is expected to be independent of age and only mildly dependent on metallicity, it is widely used as a distance indicator (see Gallart et al. 2005 and references therein). In addition, HB stars are fundamental standard candles for Population II systems, and consequently are important tools for determining ages of GCs from the main-sequence turnoff luminosity (Rich et al. 1996).

Two of the first studies of the HB for M31 GCs were those of Rich et al. (1996) and Fusi Pecci et al. (1996). They used the observed data from the WFPC2 and Faint Object Camera (FOC) onboard the HST to make the first tentative detection of HB stars in G1, B006, B045, B225, B343, B358, B405, and B468, deriving the apparent magnitude of the HB for these GCs to be in the range \(25.29 < V < 25.66\). In addition, Fusi Pecci et al. (1996) firstly presented a direct calibration for the mean absolute magnitude of the HB at the instability strip with varying metallicity for M31 GCs.

B379 was firstly detected by Sharov (1973; his reference, No. 19), and confirmed by Sargent et al. (1977; their reference, No. 312; SKHB312 was also used by Brown et al. 2004a; S312 was used by Ma et al. 2007) and Battistini et al. (1987; their reference, No. 379 is used in the Revised Bologna Catalogue, [Galleti et al. 2004, 2006, 2007] and in this article.). B379 is located in the halo of M31, at a projected distance of about 59′ (13 kpc) from the galaxy’s nucleus. B379 is a common halo GC; however, it is among the first extragalactic GCs whose age was accurately estimated by main-sequence photometry (Brown et al. 2004a) based on its CMD from the extremely deep images observed with the HST/ACS.

In this article, we redetermine the age, metallicity, reddening, and distance modulus for B379 by comparing its CMD constructed by Brown et al. (2004a) with isochrones of the Padova stellar evolutionary models. The article is organized as follows. In § 3, we describe the results of photometric data based on the HST/ACS observations for B379. In § 4, we constrain the age, metallicity, reddening value, and distance modulus for B379. Finally, we give a summary in § 5.

2. RECENT WORKS ON B379

Brown et al. (2004a) used main-sequence photometry to determine the age of B379 based on the CMD constructed using the extremely deep images from the HST/ACS observations. This CMD reached more than 1.5 mag below the main-sequence turnoff, and was the first CMD that allowed a direct age estimate from the turnoff for an extragalactic cluster. By comparison to isochrones of VandenBerg et al. (2006), Brown et al. (2004a) derived the age of B379 to be \(10^{+2.5}_{-1.0}\) Gyr. Ma et al. (2007) determined the age of B379 by comparing its multicolor photometric data which included the near-ultraviolet (NUV) from the Nearby Galaxies Survey (NGS) of the Galaxy Evolution Explorer (GALEX) (Rey et al. 2005, 2007), broadband \(UBVR\) (Battistini et al. 1987; Reed et al. 1994), 9 BATC intermediate-band filters and Two Micron All Sky Survey (2MASS) \(JHK\), and the SSP models of BC03. These photometric data constitute the SEDs of B379 covering 2267 Å–20000 Å. The age of B379 determined by Ma et al. (2007) is \(9.5^{+1.15}_{-0.99}\) Gyr, which is consistent with the determination of \(10^{+2.5}_{-1.0}\) Gyr by Brown et al. (2004a). However, BC03 models are based on the Padova evolutionary tracks. So it is necessary to compare the age scales of the Padova evolutionary tracks and the Victoria-Regina isochrones used in Brown et al. (2004a), and only if these two evolutionary tracks have consistent age scales for B379 will a comparison between Brown et al. (2004a) and Ma et al. (2007) be meaningful. For example, Ma et al. (2007) drew the isochrones with 10 Gyr and the solar metallicity, and found a very good match in the main sequence and the subgiant branch (SGB) (see Ma et al. 2007 for details). However, we should check whether the age of B379 can be estimated to be \(\sim 10\) Gyr based on the Padova evolutionary tracks. This is one of the key contributions of the present article.

3. DATABASE

The observed data for B379 used in this study are from Brown et al. (2004a), who constructed the CMD of B379 using images from the ACS observations in the F606W and the F814W filters. Using the ACS Wide Field Channel (WFC),
Brown et al. (2003) obtained deep optical images of a field 51’ from the nucleus on the southeast minor axis of the M31 halo that includes B379, which is 39.1 hr in the F606W filter and 45.4 hr in the F814W filter. Brown et al. (2004a) presented the CMD of B379 based on these ACS observations. The resulting CMD, which reached $m_V \approx 30.5$ mag, is the first CMD of extragalactic clusters reaching more than 1.5 mag below the main-sequence turnoff. These observations allow the first direct age estimate from the turnoff for an extragalactic cluster. From comparison with the isochrones of VandenBerg et al. (2006), Brown et al. (2004a) derived the age of B379 to be $10^{+2.5}_{-1.0}$ Gyr. In Brown et al. (2004a), the CMD of B379 was constructed from stars within an annulus chosen to maximize the signal-to-noise ratio and minimize field contamination. Because B379 was near the field edge and the observations were dithered, the exposure time was not uniform across the annulus. Brown et al. (2004a) thus discarded the fraction of annulus (<0.5%) that had half of the total exposure time and kept the fraction (<14%) that was exposed for 75% of the total exposure time. In addition, Brown et al. (2004a) used extensive artificial star tests to determine the photometric scatter and completeness as a function of color, luminosity, and field position. Finally, 1720 stars within the annulus spanning 100–300 pixels were retained to produce a much cleaner CMD (see Brown et al. 2004a for details). In this article, we take these 1720 stars as the member stars of B379 as Brown et al. (2004a) did (The data were kindly provided by Dr. Brown).

4. THE AGE, METALLICITY, REDDENING, AND DISTANCE MODULUS OF B379

4.1. Isochrones of Stellar Evolutionary Models

More than 50 years ago, Sandage (1953) presented the CMD for the Galactic GC M3 and applied an evolutionary theory to the CMD to give a time interval of $5 \times 10^9$ yr since the formation of the main sequence. From then on, main-sequence photometry has been considered the most direct method for determining ages of stars clusters, because the turnoff of the CMD is mostly affected by age (see Puzia et al. 2002b and references therein). Stellar evolutionary models from the Padova group (Bertelli et al. 1994; Girardi et al. 2000, 2002 and references therein) and the Victoria-Regina (VandenBerg et al. 2000, 2006 and references therein) are widely used. In the Padova stellar evolutionary models, Girardi et al. (2002) provided tables of theoretical isochrones in such photometric systems as ABmag, STmag, Vegamag, and a standard star system, and derived tables of bolometric corrections for the Johnson-Cousins-Glass, $HST$/WFPC2, $HST$/NICMOS, Washington, and ESO Imaging Survey systems. The complete database (Girardi et al. 2002) covers a very large range of stellar masses (typically from 0.6 to 120 $M_\odot$). As a supplement, Girardi et al. (2008) presented several theoretical isochrones including $HST$/ACS WFC. These models (Girardi et al. 2002, 2008) are computed with updated opacities and equations of state, and moderate amount of convective overshoot. However, the isochrones are presented for only 6 initial chemical compositions: [Fe/H] = $-2.2490, -1.6464, -0.6392, -0.3300, +0.0932$ (solar metallicity), and $+0.5595$, which are evidently not dense enough. It is fortunate that Marigo et al. (2008) provide tables for intermediate values of age and metallicity via an interactive interface. We will discuss this resource in detail in § 4.2. The novel feature of the Victoria-Regina models (VandenBerg et al. 2000, 2006 and references therein) is that they provide a wide range of metallicities; i.e., VandenBerg et al. (2006) presented 72 grids of stellar evolutionary tracks for 32 [Fe/H] values from $-2.31$ to 0.49, which are dense enough for studying properties of stellar populations with different metallicities. In addition, in these models, convective core overshooting has been treated using a parameterized form of the Roxburgh criterion (Roxburgh 1978, 1989), in which the free parameter, $F_{ov}$ ($F_{ov}$ must be calibrated using observations), is assumed to be a function of both mass and metal abundance.

4.2. Isochrone Fitting

To determine the main characteristics (age and metallicity) of the population in B379, we fit isochrones to the cluster CMD. We used the Padova theoretical isochrones in the $HST$/ACS WFC STmag system (Marigo et al. 2008). Via the interactive interface noted in § 4.1., we can construct a grid of isochrones for different values of age and metallicity, photometric system, and dust properties. We use the default models that involve scaled solar abundance ratios (i.e., $[\alpha/Fe] = 0.0$). The Salpeter initial mass function (IMF) (Salpeter 1955) is adapted to match the selection of Ma et al. (2007), who used the high-resolution SSP models of BC03, computed using the Salpeter (1955) IMF; circumstellar dust is not included. As we pointed out previously, by comparison to isochrones of VandenBerg et al. (2006), Brown et al. (2004a) derived the age of B379 to be $10^{+2.5}_{-1.0}$ Gyr. In addition, the metallicity of B379 is available: Huchra et al. (1991) derived $[Fe/H] = -0.7 \pm 0.35$ using the strengths of six absorption features in the cluster integrated spectra; Holland et al. (1997) used the $HST$/WFPC2 photometry to construct the deep CMD for B379, and the shape of the red giant branch (RGB) gave an iron abundance of $[Fe/H] = -0.53 \pm 0.03$. These metallicities obtained from different methods are consistent. Based on the age and metallicity of B379 obtained by the previous authors (Brown et al. 2004a; Huchra et al. 1991; Holland et al. 1997), we used the interactive tables noted in § 4.1 to construct a fine grid of isochrones about ages and metallicities, sampling an age range $8.0 \leq \tau \leq 13.5$ Gyr at intervals of 0.5 Gyr, and a metal abundance range 0.00250 $\leq Z \leq 0.00950$ at intervals of 0.00025 dex. The total metallicity $[M/H] = \log{(Z/Z_\odot)}$ where

\footnote{At http://stev.oapd.inaf.it/cmd.}
$Z_\odot \approx 0.019$, so this abundance range corresponds to $-0.88 \leq [\text{M/H}] \leq -0.30$.

We followed the method of Mackey & Broby Nielsen (2007) of finding the best-fitting isochrone, by locating by eye three fiducial points on the CMD of the cluster: the magnitude and color of the turnoff, the magnitude of the tight clump of red HB stars, and the color of the RGB at a level 3.0 mag brighter than the level of the turnoff. This latter point was selected simply as a point lying on the lower RGB at a level intermediate between that of the red end of the SGB and that of the tight clump of red HB. We then calculated the difference in magnitude between the level of the turnoff and the level of the tight clump of red HB ($\Delta m_{\text{F814W}}$), and the difference in color between the turnoff and the RGB fiducial point ($\Delta c_{\text{F814W}}$). As Mackey & Broby Nielsen (2007) pointed out, the difference in magnitude between the level of the turnoff and the level of the tight clump of red HB is strongly sensitive to cluster age (and weakly sensitive to cluster metallicity), while the difference in color between the turnoff and the RGB fiducial point is sensitive to both cluster age and metallicity. We determined $\Delta m_{\text{F814W}} = 3.77 \pm 0.1$ and $\Delta c_{\text{F814W}} = 0.28 \pm 0.01$.

Second, we calculated the same intervals for all isochrones on the grid, and selected only those with values lying within certain tolerances of the cluster measurements. In this article, we adopted $\pm 0.2$ mag for $\Delta m_{\text{F814W}}$ and $\pm 0.02$ mag for $\Delta c_{\text{F814W}}$. We fit the selected isochrones to the CMD by eye. At the same time, we calculated the offsets in magnitude and color required to align the turnoff of the isochrone with that of the CMD, and the offsets in magnitude required to align the tight clump of red HB of the isochrone with that of the CMD, and the offsets in color required to align the RGB fiducial point of the isochrone with that of the CMD. We then averaged the offsets in magnitude and in color and applied them to overplot the isochrone on the CMD, and identified the best-fitting isochrone by eye. The resulting offsets $\delta m_{\text{F814W}}$ and $\delta c_{\text{F814W}}$ provide estimates for the distance modulus to B379 ($(m-M)_0$) and the reddening value $(E(B-V))$: $\delta m_{\text{F814W}} = (m-M)_0 + A_{\text{F814W}}$, and $\delta c_{\text{F814W}} = A_{\text{F606W}} - A_{\text{F814W}}$. The reddening law from Cardelli et al. (1989) is employed in this article. The effective wavelengths of the ACS F606W and F814W filters are $\lambda_{\text{eff}} = 5918$ and 8060 Å (Sirianni et al. 2005), so that from Cardelli et al. (1989), $A_{\text{F606W}} \approx 2.8 \times E(B-V)$ and $A_{\text{F814W}} \approx 1.8 \times E(B-V)$ (see Barmby et al. 2007 for details). The reddening value and distance modulus for B379 obtained in this article are: $E(B-V) = 0.08$ and $(m-M)_0 = 24.44 \pm 0.10$, where the uncertainty is the standard error of the mean.

The best-fitting Padova isochrone can be seen in Figure 1, with the metal abundance 0.009 in $Z$ (or $-0.325$ in [M/H]) and 11.0 Gyr in age. The age of B379 obtained in this article is $11.0 \pm 1.5$ Gyr, where the uncertainty is the standard error of the mean.

![Figure 1](image-url)

The primary purpose of this article is to obtain the age of B379 by comparing its CMD with isochrones of the Padova stellar evolutionary models, and to check whether the age of B379 we obtained is in agreement with the determination of Brown et al. (2004a). From high-resolution stellar spectroscopy, it is shown that GCs in both the halo and the bulge of our Galaxy are $\alpha$/Fe enhanced with the typical values $[\alpha$/Fe$] \approx 0.3 \pm 0.1$ dex (see Thomas et al. 2003 and references therein). For M31 GCs, the estimates of $\alpha$/Fe ratios by Beasley et al. (2005) and Puzia et al. (2005) showed it may, on average, be $\sim 0.1$–0.2 dex lower than in the Milky Way (see also Colucci et al. 2009). The Padova stellar evolutionary models do not provide isochrones with $[\alpha$/Fe$] = 0.0$; however, the luminosities of turnoff, SGB, and the tip of the RGB are nearly unchanged by varying $\alpha$ enhancement except in the intermediate-age regime, where $\alpha$-enhanced isochrones are slightly fainter than scaled solar ones (see Gallart et al. 2005 and references therein).

It is generally known that the turnoff, SGB, and lower RGB are
the most age-sensitive features of the CMD, so the age of B379 obtained based on the isochrones with $[\alpha/\text{Fe}] = 0.0$ will not change when using the isochrones with $[\alpha/\text{Fe}] > 0.0$.

### 4.3. Comparison with Previously Published Results

The age of B379 (11.0 ± 1.5 Gyr) obtained in this article is consistent with the determination (10.4 ± 1.0 Gyr) of Brown et al. (2004a). Brown et al. (2004a) determined the age of B379 by comparing the observed CMD with isochrones of VandenBerg et al. (2006). The result of this article confirmed the conclusion of Brown et al. (2004a) that B379 is 2–3 Gyr younger than the oldest Galactic GCs. The metallicity of B379 obtained in this article is $[\text{M/H}] = -0.325$. Taking into account an enhancement of the $\alpha$-capture elements by $[\alpha/\text{Fe}] = 0.3$ (Brown et al. 2004a), and using the relation between $[\text{M/H}]$, $\text{Fe/H}$, and $[\alpha/\text{Fe}]$ from Salaris et al. (1993), we derived $[\text{Fe/H}] = -0.54$, which is in good agreement with the determination of $[\text{Fe/H}] = -0.53$ of Holland et al. (1997) based on the shape of the RGB of the deep CMD observed by the HST/WFPC2.

B379 is located in the M31 halo, so the extinction is mainly from the foreground Galactic reddening in the direction of M31, which has been discussed by many authors (e.g., van den Bergh 1969; McClure & Racine 1969; Frogel et al. 1980; Fusi Pecci et al. 2005), with nearly similar values determined: e.g., $E(B-V) = 0.08$ by van den Bergh (1969), $E(B-V) = 0.11$ by McClure & Racine (1969) and Hodge (1992), and $E(B-V) = 0.08$ by Frogel et al. (1980). In addition, Barmby et al. (2000) determined the reddening for each individual cluster using correlations between optical and infrared colors and metallicity, and by defining various “reddening-free” parameters using their large database of multicolor photometry. Finally, Barmby et al. (2000) determined reddenings for 314 clusters, 221 of which are reliable (see Barmby et al. 2000 for details). For B379, Barmby et al. (2000; also P. Barmby 2002, private communication) obtained its reddening value to be $E(B-V) = 0.10 ± 0.05$. It is evident that the reddening value of $E(B-V) = 0.08$ obtained in this article is consistent with these determinations.

Given the importance of M31 as an anchor for the extragalactic distance scale, many studies have presented distance determinations to M31 using different methods. Pritchet & van den Bergh (1987), Holland (1998) and Vilardell et al. (2006) have given a detailed review. Although the stellar populations located in different positions in M31 have different distance moduli, the dispersion can be neglected since the distance of M31 is large enough. For example, Rich et al. (2005) pointed out that the clusters in M31 dispersed over a 20 kpc radius would have up to 0.06 mag random distance uncertainty. So, the distance modulus to B379 obtained in this article should be consistent with the distance of M31 previously determined within 0.06 mag random distance uncertainty.

Here we compare our determination with the most recent and/or important measurements. Freedman & Madore (1990) derived the mean distance modulus to M31 to be $(m-M)_0 = 24.44 ± 0.13$ based on the Cepheids in Baade’s fields I, III, and IV (Baade & Swope 1963, 1965) observed using the Canada-France-Hawaii Telescope (CFHT). Holland (1998) determined the distance moduli to 14 M31 GCs by fitting theoretical isochrones to the observed RGBs, including B379. The distance modulus to B379 obtained by Holland (1998) is $(m-M)_0 = 24.45 ± 0.07$. Stanek & Garnavich (1998) estimated the distance modulus to M31 as $(m-M)_0 = 24.47 ± 0.035$ by comparing the red clump stars with parallaxes known to be better than 10% in the Hipparcos catalog with the red clump stars in three fields in M31 observed with the HST. A determination of Freedman et al. (2001) based on the Cepheid period-luminosity (PL) relation suggests the distance modulus of $(m-M)_0 = 24.38 ± 0.05$ to M31 based on the results of the HST Distance Scale Key Project to measure the Hubble constant. Durrell et al. (2001) determined the distance modulus of $(m-M)_0 = 24.47 ± 0.12$ to M31 from the luminosity of the RGB tip of over 2000 RGB halo stars in a halo field located about 20 kpc from the M31 nucleus along the southeast minor axis. Joshi et al. (2003) obtained $R$- and $I$-band observations of a $13' \times 13'$ region in the disk of M31 and derived the Cepheid PL distance modulus to be $(m-M)_0 = 24.49 ± 0.11$. Brown et al. (2004b) determined the distance modulus of $(m-M)_0 = 24.5 ± 0.1$ to M31 based on brightness of 55 RR Lyrae stars detected on the HST/ACS images of $\sim$ 100 kpc exposures over 41 days). McConnachie et al. (2005) derived the distance modulus to M31 to be $(m-M)_0 = 24.5 ± 0.07$ based on the method of the tip of the RGB observed using the Isaac Newton Telescope Wide Field Camera (INT WFC). Ribas et al. (2005) derived the distance modulus of M31 as $(m-M)_0 = 24.44 ± 0.12$ from an eclipsing binary. Very recently, Sarajedini et al. (2009) presented the HST observations taken with the ACS WFC of two fields near M32 located 4–6 kpc from the center

| Method                  | $(m-M)_0$ (mag) | Reference |
|------------------------|----------------|-----------|
| Cepheids               | 24.44 ± 0.13   | (1)       |
| Red Giant Branch       | 24.45 ± 0.07   | (2)       |
| Red Clump              | 24.47 ± 0.035  | (3)       |
| Cepheids               | 24.38 ± 0.05   | (4)       |
| Red Giant Branch       | 24.47 ± 0.12   | (5)       |
| Cepheids               | 24.49 ± 0.11   | (6)       |
| RR Lyrae               | 24.5 ± 0.10    | (7)       |
| Tip of the RGB         | 24.47 ± 0.07   | (8)       |
| Eclipsing binary       | 24.44 ± 0.12   | (9)       |
| RR Lyrae               | 24.46 ± 0.11   | (10)      |
| CMD                    | 24.44 ± 0.10   | (11)      |

References.—(1) Freedman & Madore 1990; (2) Holland 1998; (3) Stanek & Garnavich 1998; (4) Freedman et al. 2001; (5) Durrell et al. 2001; (6) Joshi et al. 2003; (7) Brown et al. 2004b; (8) McConnachie et al. 2005; (9) Ribas et al. 2005; (10) Ribas et al. 2005; Sarajedini et al. 2009; (11) this article.
of M31, and identified 752 RR variables with excellent photometric and temporal completeness. Based on this large sample of M31 RR Lyrae variables, and using a relation between RR Lyrae luminosity and metallicity along with a reddening value of $E(B-V) = 0.08 \pm 0.03$, they derived the distance modulus of $(m-M)_{0} = 24.46 \pm 0.11$ to M31. For comparison, we list these determinations of M31 distance moduli in Table 1. It is evident that our determination is in good agreement with the previous determinations.

5. SUMMARY

In this article, we redetermined the age of the M31 GC B379 by fitting its deep photometry extending below the main-sequence turnoff to the isochrones of the Padova group (Girardi et al. 2002, 2008; Marigo et al. 2008). The age obtained in this article is consistent with the determination of Brown et al. (2004a), and confirms their conclusion that B379 is 2–3 Gyr younger than the oldest Galactic GC. This article also confirms the consistency in the age scales of B379 between the Padova group isochrones used here with those of the 2006 Vandenberg isochrones used by Brown et al. (2004a). Thus the comparison between the results of Brown et al. (2004a) and those of Ma et al. (2007) is meaningful. In addition, the metal abundance, reddening, and distance modulus obtained in this article are consistent with the previous determinations.

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