Chin. J. Astron. Astrophys. Vol. 4 (2004), No. 2, 125–132
(*http://www.chjaa.org* or *http://chjaa.bao.ac.cn*)

Chinese Journal of
Astronomy and
Astrophysics

Age and Mass Estimates for 41 Star Clusters in M33 *

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Received 2003 July 18; accepted 2003 December 1

Abstract In this second paper of our series, we estimate the age of 41 star clusters, which were detected by Melnick & D'odorico in the nearby spiral galaxy M33, by comparing the integrated photometric measurements with theoretical stellar population synthesis models of Bruzual & Charlot. Also, we calculate the mass of these star clusters using the theoretical M/L_V ratio. The results show that, these star clusters formed continuously in M33 from $\sim 7 \times 10^6 - 10^{10}$ years and have masses between $\sim 10^3$ and $2 \times 10^6\, M_\odot$. M33 frames were observed as a part of the BATC Multicolor Survey of the sky in 13 intermediate-band filters from 3800 to 10 000Å. The relation between age and mass confirms that the sample star cluster masses systematically decrease from the oldest to the youngest.

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

1 INTRODUCTION

Since a single star cluster is a luminous packet comprising stellar populations with a single age and chemical abundance, it can be used to study the ongoing and past star formation of the host galaxies. For example, globular clusters (GCs) can give clues about the earliest epochs of their host galaxies, and young clusters can provide insight into the chemical evolution and star formation history of the parent galaxies. In addition, studies of star cluster populations could aid our understanding of the relationship between cluster formation and the physical morphology of the host galaxies. The best-studied external systems are Magellanic Clouds (MCs) and M31. M31 has a cluster population similar to that in the Milky Way. Clusters in MCs populate almost all evolutionary phases, and occupy regions of age and metallicity not populated in our Galaxy or M31. M33 is a small Scd Local Group galaxy, about 15 times farther from us than the LMC. Hubble did the pioneer work of discovering star clusters in M33. He found that the brightest star clusters in M33 are bluer than the GCs in M31 (see details from Sharov & Lyutyi 1984). However, the study of M33 has been neglected because of its proximity to M31. Before 1982, only a few dozen cluster candidates in M33 had been detected (Hiltner

* Supported by the National Natural Science Foundation of China.

1960; Kron & Mayall 1960; Melnick & D'Odorico 1978). Then, Christian & Schommer (1982) found more than 250 nonstellar objects using 14×14 inch^2 unfiltered, unbaked, IIa-O focus plate exposed for 150 minutes with the Kitt Peak 4 m Richey-Chrétien (R-C) direct camera. Recently, Mochejska et al. (1998) detected 51 GC candidates using the data collected during the DIRECT project (Kaluzny et al. 1998; Stanek et al. 1998); especially, Chandar, Bianchi & Ford (1999a, 2001) discovered 168 star clusters from 55 deep *Hubble Space Telescope* (HST) WFPC2 fields from their program and the HST archive, 130 of which were previously unknown. We should emphasize that the high spatial resolution of HST images can easily distinguish star clusters from individual stars (for details see Chandar, Bianchi & Ford 1999a). Besides, while most candidate clusters detected from the ground-based work lie in the outskirts of the parent galaxy, the HST images allowed Chandar, Bianchi & Ford (1999a, 2001) to penetrate into the crowded, spiral regions of M33.

M33 was observed as part of galaxy calibration program of the Beijing-Arizona-Taiwan-Connecticut (BATC) Multicolor Sky Survey (Fan et al. 1996; Zheng et al. 1999) from 1995 September 23 to 2000 August 28. This program uses the 60/90 cm Schmidt Telescope at the Xinglong Station of the National Astronomical Observatories, and has a custom-built set of 15 intermediate-band filters to do spectrophotometry for pre-selected 1 deg^2 regions of the northern sky. The BATC Schmidt telescope is equipped with a Ford 2048×2048 Ford CCD at its main focus. Using the 13 intermediate-band filter images of M33 obtained by the BATC Multicolor Sky Survey, Ma et al. (2001, 2002a, 2002b, 2002c) estimated the ages of 180 star clusters in M33. These star clusters are from four survey samples, namely, Sarajedini et al. (1998, 2000), Mochejska et al. (1998), and Chandar, Bianchi & Ford (1999a, 2001). Sarajedini et al. (1998, 2000) estimated 10 halo GCs metallicities using the shape and color of the red giant branch. The data are based on HST Wide-Field Planetary Camera 2 observations in the F555W and F814W filters. Mochejska et al. (1998) detected 51 GC candidates using the data collected during the DIRECT project, in which the observations of M33 were done with the 1.2 m telescope at the F. L. Whipple Observatory equipped a thinned, back-side illuminated, AR-coated Loral 2048×2048 CCD. Chandar, Bianchi & Ford (1999a, 2001) detected 168 star clusters from 55 deep HST WFPC2 fields. In this paper, we estimate the ages and masses for 41 M33 star clusters that were detected by Melnick & D'odorico (1978) based on the multicolor photometry of Ma et al. (2002d, hereafter Paper I)

The outline of the paper is as follows. A brief description of the observations and data reduction is presented in Sect. 2. In Sect. 3, we provide a brief description of the stellar population synthesis models of Bruzual & Charlot (1996, hereafter BC96, unpublished). The ages and masses for the star clusters are estimated in Sect. 4. A summary is presented in Sect. 5.

2 SAMPLE STAR CLUSTERS, OBSERVATIONS AND DATA REDUCTION

The 41 sample star clusters in M33 in this paper are from Paper I, where we have presented their accurate positions using the HST Guide Star Catalog, their guiding charts, and their spectral energy distributions (SEDs) in 13 intermediate-band filters from 3800 to 10 000Å. These clusters were detected by Melnick & D'Odorico (1978).

Large field multicolor observations of M33 were obtained in the BATC photometric system. The whole optical body of M33 was accumulated in 13 intermediate-band filters with a total exposure time of about 38 hours. The dome flat-field images were taken by using a diffuse plate in front of the correcting plate of the Schmidt Telescope. For flux calibration (see Zhou et al.

2001 and Yan et al. 1999 for a detail), the Oke-Gunn primary flux standard stars HD19445, HD84937, BD+262606 and BD+174708 were observed during photometric nights.

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

For each sample cluster, the PHOT routine in DAOPHOT (Stetson 1987) is used to obtain the magnitudes. To avoid contamination from nearby objects, we adopt a small aperture of $6.8''$ corresponding to a diameter of four pixels in the Ford CCDs. Aperture corrections are computed using isolated stars.

3 DATABASES OF SIMPLE STELLAR POPULATIONS

Since the pioneering work of Tinsley (1972) and Searle, Sargent & Bagnuolo (1973), evolutionary population synthesis model has become a standard technique to study the stellar populations of galaxies. A comprehensive compilation of such models was presented by Leitherer et al. (1996) and Kennicutt (1998). Widely used models for star forming galaxies include those of Bruzual & Charlot (1993, 1996), Bertelli et al. (1994), Fioc & Rocca-Volmerange (1997), Schaerer & Vacca (1998), and Leitherer et al. (1999).

As we know, a simple stellar population (SSP), which is defined as a single generation of coeval stars with fixed parameters such as age, metallicity, and initial mass function, is suitable for studying the stellar populations of a star cluster. So, in this paper we use the SSPs of BC96 (Galaxy Isochrone Synthesis Spectra Evolution Library) to study the integrated properties of M33 star clusters.

3.1 Integrated Colors of BC96

Charlot & Bruzual (1991) developed a model of stellar population synthesis, which allows an accurate can be used determination of the distribution of stars in the theoretical color-magnitude diagram for any stellar system. Then, Bruzual & Charlot (1993) presented "isochrone synthesis" as a natural and reliable approach to model the evolution of stellar populations in star clusters and galaxies, with which the authors computed the SEDs of stellar populations with solar metallicity. In BC96, Bruzual & Charlot improved their models (1993), and provided the SEDs of stellar populations for a wide range of stellar metallicity, $Z = 0.0004$, 0.004, 0.008, 0.02, 0.05, 0.1.

Since the observational data are integrated luminosities, we need to convolve the SEDs of BC96 with the BATC filter profiles to obtain the optical and near-infrared integrated luminosity for comparisons (Kong et al. 2000). The integrated luminosity $L_{\lambda_i}(t, Z)$ of the ith BATC filter can be calculated with

$$L_{\lambda_i}(t, Z) = \frac{\int F_\lambda(t, Z)\varphi_i(\lambda)d\lambda}{\int \varphi_i(\lambda)d\lambda}, \tag{1}$$

where $F_\lambda(t, Z)$ is the SED of the BC96 of metallicity Z at age t, and $\varphi_i(\lambda)$ is the response function of the ith filter of the BATC filter system ($i = 3, 4, \cdots, 15$). To avoid using distance-dependent parameters, we calculate the integrated colors of BC96 relative to the BATC filter BATC08 ($\lambda = 6075$Å)

$$C_{\lambda_i}(t, Z) = L_{\lambda_i}(t, Z)/L_{6075}(t, Z)\,. \tag{2}$$

4 RESULTS

4.1 Cluster Ages

In order to obtain the intrinsic colors and hence ages of the 41 M33 star clusters, the photometric measurements must be de-reddened. Following Chandar, Bianchi & Ford (2001), we adopted $E_{(B-V)} = 0.10$. Further, we adopted the extinction curve presented by Zombeck (1990). An extinction correction $A_\lambda = R_\lambda E_{(B-V)}$ was applied; here R_λ was obtained by interpolating the Zombeck data.

We will be modelling the stellar populations of the clusters by SSPs, and the cluster intrinsic colors are determined by two parameters: age and metallicity. We will determine the age and the best-fit metallicity simultaneously by a least-squares method, by minimizing the difference between the intrinsic and integrated colors of BC96

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

where $C_{\lambda_i}^{\rm ssp}(t,Z)$ represents the integrated color in BC96 and $C_{\lambda_i}^{\rm intr}(n)$ is the intrinsic integrated color for the nth star cluster. Using the stellar evolutionary models (Bertelli et al. 1994) and published line indices of 22 M33 older clusters, Chandar, Bianchi & Ford (1999b) narrowed the range of cluster metallicities (Z) to from ~ 0.0002 to 0.03. So, we only selected three BC96 models for metallicities 0.0004, 0.004 and 0.02.

Table 1 lists the ages from the different models. We also include in Table 1 the parameter R^2 of Eq. (3). The age of each cluster for the smallest R^2 is adopted, being the best overall fit.

Figure 1 shows, for the 41 clusters, the intrinsic integrated colors of the cluster (filled circles) and the integrated colors of the best-fit SSP of BC96 (thick line). Note that Cluster No.7 has strong emission lines, but these were not used in the fitting.

Figure 2 presents a histogram of age for the 41 star clusters. The results show that in general M33 star clusters have been forming continuously, with ages ranging from $\sim 4 \times 10^6$ yr to 10^{10} yr.

4.2 Cluster Masses

Star cluster masses can be calculated by comparing the measured luminosity in V band with the theoretical mass-to-light ratios. These ratios are primarily a function of the cluster age. BC96 calculated these ratios for metallicities $Z = 0.0004, 0.004, 0.008, 0.02, 0.05$, and 0.1. The measured luminosity in V band is from Paper I (V(BATC) magnitudes). At last we obtain the masses for our sample star clusters, listed in the ninth column of Table 1. Figure 3 plots the distribution of cluster masses. From Table 1 and Fig. 3 we can see that the cluster masses range from $\sim 10^3$ to $2 \times 10^6\, M_\odot$. For comparison, Galactic GCs have an average mass $\sim 10^5\, M_\odot$ (Lang 1992) with a range between $\sim 2 \times 10^3$ and $2 \times 10^6\, M_\odot$. The old M33 star clusters (such as the sample clusters 3, 5, 8, 9, 13, 18, 21, 49, 53, and 57) have masses similar to typical Galactic GC values.

In Fig. 4 we plot age versus mass for our sample star clusters. It is clear that, for the M33 clusters, the mass decreases systematically from the oldest to the youngest.

Table 1 Age and Mass Estimates for M33 Clusters

	Age [log yr]	R^2	Age [log yr]	R^2	Age [log yr]	R^2	Age [log yr]	Mass ([log $M_\odot$])
No.	$Z = 0.0004$		$Z = 0.004$		$Z = 0.02$		adopted	
1	8.56	0.0199	7.54	0.0231	7.44	0.0428	8.56	4.53
2	8.01	0.1734	6.90	0.1916	6.76	0.2059	8.01	3.77
3	10.30	0.4768	10.04	0.2483	9.38	0.3283	10.04	6.16
4	7.96	0.0715	6.88	0.0916	6.76	0.0940	7.96	3.79
5	10.30	0.5174	10.22	0.1176	9.40	0.1892	10.22	5.43
6	6.62	0.1008	6.96	0.0940	8.06	0.1019	6.96	3.20
7	8.46	1.0910	8.56	0.9995	6.96	0.7665	6.96	3.03
8	10.20	0.0315	9.48	0.0409	9.01	0.1155	10.20	5.43
9	10.30	1.0022	10.30	0.1398	9.78	0.1247	9.78	6.20
10	8.21	0.0434	7.86	0.0296	7.91	0.0424	7.86	4.24
13	10.05	0.1838	9.36	0.1870	9.01	0.1955	10.05	5.54
16	7.74	0.2391	6.82	0.2448	6.76	0.2499	7.74	3.90
18	10.30	1.8351	10.30	0.5072	10.00	0.2560	10.00	6.11
19	8.36	0.0235	7.44	0.0352	6.90	0.0265	8.36	4.38
21	10.30	0.2419	10.03	0.0540	9.38	0.0725	10.03	5.65
23	9.01	0.0792	7.54	0.1797	8.41	0.2489	9.01	4.41
27	8.71	0.0183	7.70	0.0114	7.65	0.0262	7.70	4.47
28	8.06	0.0580	7.28	0.0336	6.86	0.0338	7.28	3.85
29	8.51	0.0990	8.46	0.1050	7.18	0.1073	8.51	4.19
31	8.01	0.0527	6.92	0.0580	6.84	0.0854	8.01	4.10
32	8.86	0.0906	7.56	0.1068	8.36	0.1547	8.86	4.47
33	8.36	0.0138	8.26	0.0151	8.16	0.0203	8.36	4.31
34	8.51	0.0678	8.51	0.0547	7.06	0.0545	7.06	3.61
35	8.06	0.1206	7.34	0.1361	6.88	0.1043	6.88	3.41
36	8.51	0.1142	8.56	0.0359	7.00	0.0413	8.56	4.40
37	8.06	0.0439	6.98	0.0339	8.06	0.0392	6.98	3.82
38	9.06	0.1171	8.81	0.0965	7.00	0.1379	8.81	4.67
39	8.06	0.0337	6.96	0.0183	8.06	0.0280	6.96	3.49
40	6.62	0.0400	6.96	0.0193	6.86	0.0333	6.96	3.77
41	8.51	0.0919	8.56	0.0466	8.56	0.0355	8.56	4.44
43	8.21	0.0484	8.01	0.0303	8.01	0.0251	8.01	4.22
44	10.30	0.3302	9.51	0.3189	9.11	0.2278	9.11	5.05
45	9.36	0.0206	9.01	0.0164	8.81	0.0462	9.01	4.90
46	8.91	0.0176	8.76	0.0384	8.46	0.0622	8.91	4.75
49	10.30	0.3714	10.13	0.0834	9.40	0.0898	10.13	5.63
50	9.54	0.2186	9.06	0.1206	8.81	0.0885	8.81	4.53
52	9.26	0.0395	8.96	0.0967	8.76	0.1667	9.26	5.60
53	10.30	2.3277	10.30	0.7618	10.14	0.3634	10.14	6.32
54	8.91	0.0449	8.76	0.0292	8.51	0.0409	8.76	4.89
56	8.06	0.0181	7.36	0.0190	7.74	0.0273	8.06	4.72
57	10.30	0.2079	10.02	0.0179	9.38	0.0350	10.02	5.88

Using the Battinelli & Capuzzo-Dolcetta (1989) theoretical mass-to-light ratios in V band, Chandar et al. (1999b) also estimated masses for the 44 M33 star clusters. Our results are in agreement with Chandar et al. (1999b) except that the highest masses are a little different, i.e., the highest masses obtained in this paper are higher than those obtained by Chandar et al. (1999b). The reason may be the different theoretical mass-to-light ratios adopted. By the way, we note that the relation shown in Fig. 4 may be biased by the inclusion of an old cluster population with a mass falling below the detection threshold.

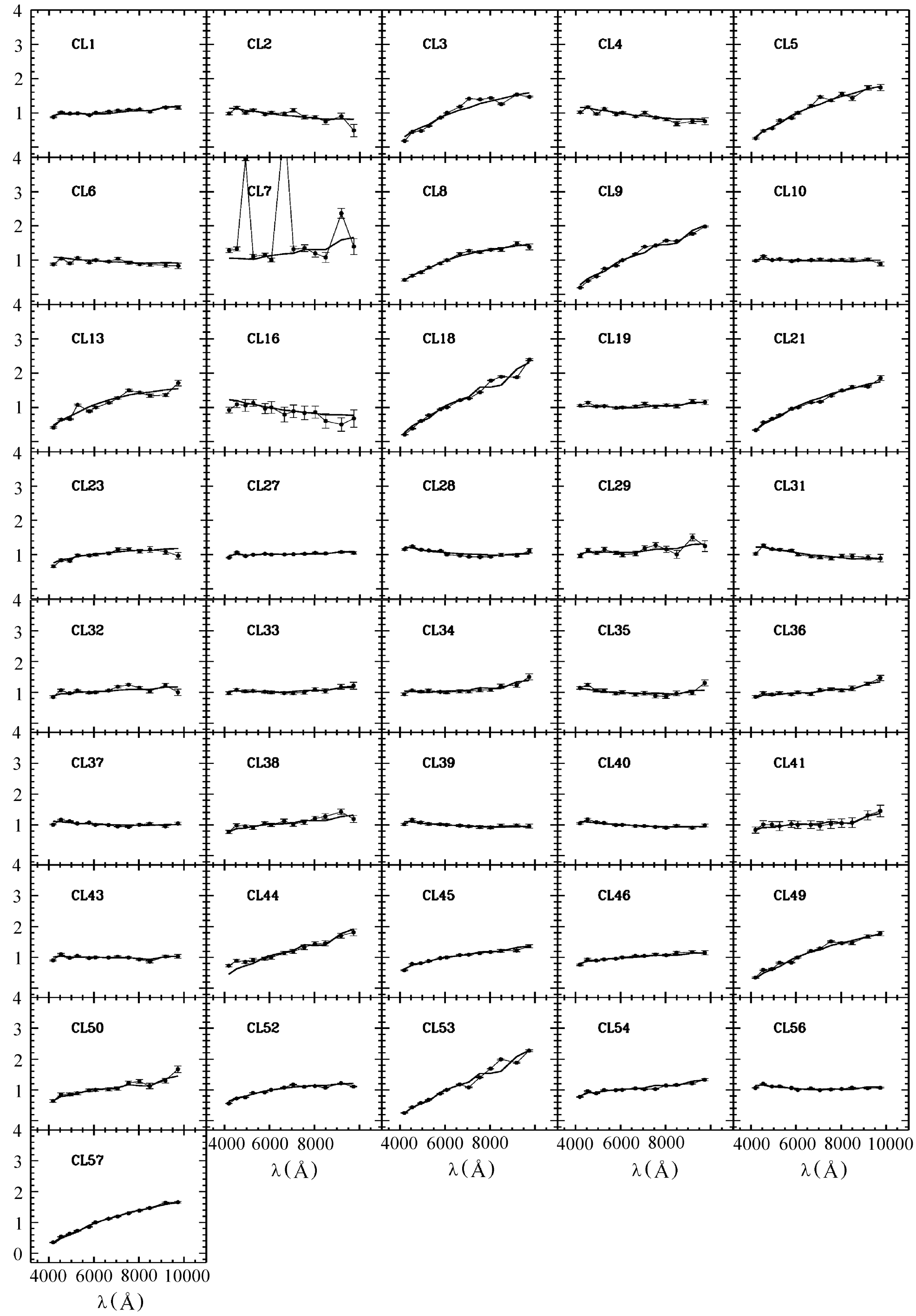

Fig. 1 Best-fit SSP integrated color (thick line) and the intrinsic integrated color of the cluster for 41 clusters.

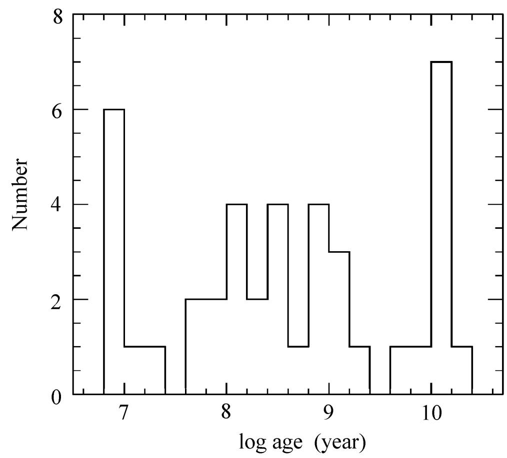

Fig. 2 Age distribution for 41 star clusters in M33.

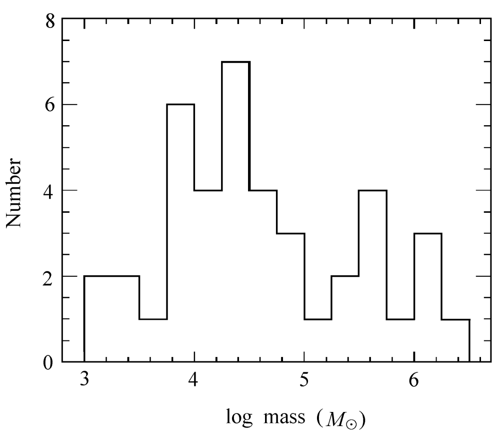

Fig. 3 Mass distribution for 41 star clusters in M33.

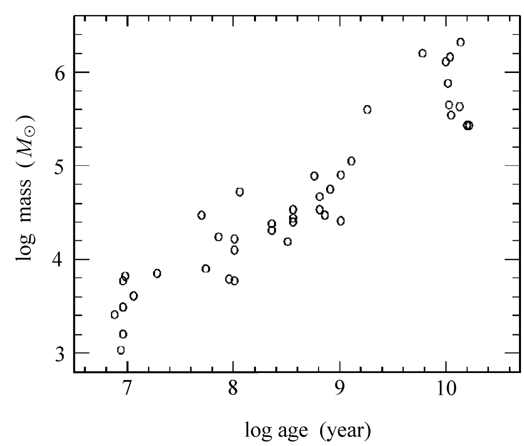

Fig. 4 Age vs. mass for the M33 star clusters.

5 SUMMARY

In this paper, we have, for the first time, estimated the ages and masses for the 41 star cluster detected by Melnick & D'odorico (1978) in the nearby spiral galaxy M33. We summarize our main conclusions as follows.

1) We estimated the ages for the 41 M33 star clusters by comparing the integrated photometric measurements with the theoretical stellar population synthesis models of BC96. The derived ages show that the clusters formed continuously from $\sim 7 \times 10^6 - 10^{10}$ years.

2) We calculated the masses for these star clusters using the theoretical M/L_V ratios. The results show that the sample clusters have masses between $\sim 10^3$ and $2 \times 10^6\ M_\odot$.

3) The relation between age and mass confirms the finding of Chandar et al. (1999b) that old clusters are more massive than young ones in this galaxy.

Acknowledgements This work has been supported by the National Key Basic Research Science Foundation (NKBRSF TG199075402) and in part by the National Natural Science Foundation of China.

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