The Optical Gravitational Lensing Experiment.
Age of Star Clusters from the SMC

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ABSTRACT

We present determination of age of clusters from 2.4 square degree region of the SMC bar. The photometric data were taken from the $BVI$ maps of the SMC and catalog of clusters in this galaxy obtained during the OGLE-II microlensing survey.

For 93 well populated SMC clusters their age is derived with the standard procedure of isochrone fitting. The distribution of age of cluster from the SMC is presented. It indicates either non-uniform process of cluster formation or very effective disruption of clusters.

1 Introduction

Studies of star clusters provide important information about parent galaxy and processes connected with their formation and evolution. The rich system of clusters from the SMC is especially well suited for such investigations. In particular, based on the age distribution of clusters one can look into the cluster formation history and obtain information on processes of cluster formation and disruption.

Unfortunately the SMC was neglected photometrically for years. Until recently only a few papers presented precise photometric data obtained with modern observational techniques for clusters from this galaxy. A few old clusters from the SMC were studied using the HST telescope (Mighell et al. 1998). Analysis of other SMC clusters can be found very sporadically in the literature. As a result precise age of the SMC clusters based on good photometric data has been derived for very limited group of objects.

Information about the age of clusters from the SMC is based mostly on indirect methods like integrated photometry or calibration of brightness of

*Based on observations obtained with the 1.3 m Warsaw telescope at the Las Campanas Observatory of the Carnegie Institution of Washington.
the brightest star. However, the method of deriving the age from integrated photometric data may be affected by several sources of uncertainty (Girardi et al. 1995).

In this paper we present new, homogeneous determination of age of 93 clusters from the center of the SMC. After presentation of the observational data, the procedure of deriving the mean reddening and age is described followed by discussion of distribution of age of the SMC clusters.

2 Observational Data

The observational data used in this paper were collected during the OGLE-II microlensing search with the 1.3-m Warsaw telescope located at the Las Campanas Observatory, Chile, which is operated by the Carnegie Institution of Washington. Eleven slightly overlapping fields located in the center of the SMC were observed. About 2.2 million stars were monitored since June 1997. The photometric data were calibrated to the standard $BVI$ system based on a few hundred observations of standard stars from Landolt (1992) fields. The typical uncertainty of photometric calibration was about 0.01 mag. Astrometric position of every star was also derived with typical accuracy of 0.1 arcsec. Details on the OGLE-II project can be found in Udalski, Kubiak and Szymański (1997). The comprehensive description of photometric and astrometric data is given by Udalski et al. (1998b). Using these data the catalog of star clusters was constructed by Pietrzyński et al. (1998). Altogether 238 objects were found. 72 of them are newly discovered clusters.

The catalog of clusters in the SMC is very well suited for studies of properties of population of clusters from the SMC. In this paper we present age determination of large sample of objects from this catalog.

3 Age of the SMC Clusters

3.1 Interstellar Reddening

Recently Paczyński and Stanek (1998) proposed a new method of distance determination based on the mean $I$-band brightness of the red clump stars. Red clump stars seem to form a very homogeneous group of objects. Their mean $I$-band magnitude does not depend on age for stars younger than 10 Gyr, and weakly depends on metallicity (Udalski 1998a,b). Large num-
ber of these stars allows to derive their mean $I$-band magnitude with high precision. Recent calibration based on Hipparcos measurements of a few hundred nearby red clump stars makes these objects the best calibrated standard candles. Red clump stars were used for modeling the galactic bar (Stanek et al. 1997) and determining the distances to the Magellanic Clouds (Udalski et al. 1998a). They can also be used as a reference for interstellar extinction determination. For example, Stanek (1996) presented the extinction map of the Baade’s Window in the Galactic bulge determined with this method.

\begin{align}
\hat{n}(I) &= a + b(I - I^\text{max}) + c(I - I^\text{max})^2 + \frac{N_{RC}}{\sigma_{RC}^2}\sqrt{2\pi} \exp\left[ -\frac{(I - I^\text{max})^2}{2\sigma_{RC}^2} \right] \\
\text{where } N_{RC}, \sigma_{RC}^2 \text{ and } I^\text{max} \text{ are the number of red clump stars, their standard deviation of brightness and maximum brightness, respectively. Fig. 1 shows exemplary histograms with fitted function given by Eq. (1) obtained for regions located around three clusters. It is clearly seen that the well pronounced red clump allows for reliable fit and thus precise determination of}
\end{align}
its mean $I$-band brightness. Assuming that extinction free brightness of the red clump stars in the SMC is equal to $I = 18.34$ mag (Udalski 1998b) and standard extinction curve ($A_I = 1.96 \cdot E(B - V)$, $E(V - I) = 1.28 \cdot E(B - V)$, Schlegel, Finkbeiner and Davis 1998) we derived extinction in the $I$-band as well as $E(V - I)$ and $E(B - V)$ reddenings. The results are given in Table 1.

### 3.2 Age Determination

Clear distinction between cluster and field stars is difficult in the dense regions in the center of the SMC. Because the color-magnitude diagrams (CMD) of fields around clusters very often resemble CMDs of clusters we decided to perform statistical subtraction of field stars from the cluster CMD. A procedure described by Mateo and Hodge (1986) was adopted.

After correction for reddening and field star subtraction we derived ages using standard procedure of isochrone fitting. We were able to fit reasonably isochrones for 93 objects from the OGLE catalog of clusters (Pietrzyński et al. 1998). The remaining clusters are too poorly populated or located in very dense stellar regions making reliable fit impossible.

The isochrones were taken from the library of Bertelli et al. (1994). These isochrones are derived from stellar models computed with the radiative opacities of Iglesias et al. (1992) and cover wide range of chemical composition and stellar masses.

The metallicity of the SMC was assumed to be $Z = 0.004$. In the case of NGC 330 the models with $Z = 0.008$ were used. We adopted the short distance scale to the SMC, namely distance modulus of 18.65 mag (Udalski 1998b).

Results of age determination are presented in Table 1. The first column contains name of cluster. In the second and third columns equatorial coordinates are given. Cluster radius, the mean reddening toward the cluster, $E(B - V)$, and determined age are presented in columns 4, 5 and 6 respectively.

Accuracy of our procedure of age determination depends on the age and richness of a given cluster. For young objects as well for those possessing few stars a wide variety of isochrones may be fitted. The age of older clusters having turn-off point close to detection limit of our photometry is also less accurate. We estimated accuracy of age determination as half of the age difference between two marginally fitting isochrones selected around the best fit isochrone. The error of age determination is given in the last column of
## Table 1

Age of the SMC clusters

| Name | OGLE-CL- | \(\alpha_{2000}\) | \(\delta_{2000}\) | \(\text{Radius}[^{\prime}]\) | \(E(B-V)\) | \(\log t\) | \(\sigma_{\log t}\) |
|------|----------|-----------------|-----------------|----------------|----------------|----------------|----------------|
| SMC0002 | 0°37\,m3\,s06 | −73°36′22′′6 | 47 | 0.06 | 8.4 | 0.1 |
| SMC0003 | 0°37\,m42\,s24 | −73°54′29′′5 | 42 | 0.10 | > 9 | − |
| SMC0008 | 0°40\,m30\,s54 | −73°24′10′′4 | 43 | 0.07 | 8.0 | 0.1 |
| SMC0009 | 0°40\,m44\,s11 | −73°32′00′′2 | 36 | 0.07 | 8.0 | 0.1 |
| SMC0011 | 0°41\,m06\,s16 | −73°21′07′′1 | 36 | 0.08 | 7.9 | 0.1 |
| SMC0012 | 0°41\,m23\,s78 | −72°53′27′′1 | 61 | 0.06 | > 9 | − |
| SMC0013 | 0°42\,m22\,s37 | −73°44′03′′1 | 23 | 0.05 | 7.3 | 0.3 |
| SMC0015 | 0°42\,m54\,s13 | −73°17′37′′0 | 30 | 0.10 | 8.1 | 0.1 |
| SMC0016 | 0°42\,m58\,s46 | −73°10′07′′2 | 42 | 0.08 | 8.3 | 0.1 |
| SMC0017 | 0°43\,m32\,s74 | −73°26′25′′4 | 26 | 0.10 | 7.9 | 0.1 |
| SMC0018 | 0°43\,m37\,s57 | −73°26′37′′9 | 26 | 0.10 | 7.9 | 0.1 |
| SMC0019 | 0°43\,m37\,s59 | −72°57′30′′9 | 12 | 0.08 | 8.6 | 0.1 |
| SMC0020 | 0°43\,m37\,s89 | −72°58′48′′3 | 9 | 0.08 | 8.6 | 0.1 |
| SMC0025 | 0°45\,m13\,s88 | −73°13′09′′2 | 15 | 0.12 | 8.0 | 0.1 |
| SMC0032 | 0°45\,m54\,s33 | −73°30′24′′2 | 30 | 0.10 | 8.0 | 0.1 |
| SMC0033 | 0°46\,m12\,s26 | −73°23′34′′0 | 18 | 0.15 | 7.2 | 0.2 |
| SMC0038 | 0°47\,m06\,s15 | −73°15′24′′9 | 21 | 0.12 | 8.1 | 0.2 |
| SMC0039 | 0°47\,m11\,s61 | −73°28′38′′1 | 49 | 0.11 | 8.0 | 0.1 |
| SMC0043 | 0°47\,m52\,s38 | −73°13′20′′3 | 22 | 0.09 | 8.5 | 0.1 |
| SMC0045 | 0°48\,m00\,s68 | −73°29′10′′3 | 35 | 0.07 | 8.4 | 0.1 |
| SMC0047 | 0°48\,m28\,s14 | −72°59′00′′3 | 36 | 0.12 | 7.8 | 0.1 |
| SMC0049 | 0°48\,m37\,s47 | −73°24′53′′2 | 38 | 0.06 | 7.0 | 0.2 |
| SMC0050 | 0°48\,m59\,s02 | −73°09′03′′8 | 14 | 0.12 | 8.3 | 0.1 |
| SMC0054 | 0°49\,m17\,s60 | −73°22′19′′8 | 27 | 0.10 | 8.0 | 0.1 |
| SMC0058 | 0°49\,m45\,s43 | −72°51′58′′0 | 36 | 0.17 | 8.3 | 0.1 |
| SMC0059 | 0°50\,m16\,s06 | −73°01′59′′6 | 25 | 0.10 | 7.8 | 0.1 |
| SMC0060 | 0°50\,m21\,s95 | −73°23′16′′5 | 36 | 0.08 | 8.4 | 0.1 |
| SMC0061 | 0°50\,m00\,s26 | −73°15′17′′7 | 21 | 0.12 | 7.4 | 0.2 |
| SMC0064 | 0°50\,m39\,s55 | −72°57′54′′8 | 36 | 0.10 | 8.1 | 0.1 |
| SMC0066 | 0°50\,m55\,s39 | −73°12′11′′0 | 17 | 0.09 | 7.8 | 0.1 |
| SMC0067 | 0°50\,m55\,s54 | −72°43′59′′7 | 42 | 0.08 | 8.2 | 0.1 |
| SMC0068 | 0°50\,m56\,s26 | −73°17′21′′1 | 55 | 0.09 | 7.7 | 0.2 |
| SMC0069 | 0°51\,m14\,s13 | −73°06′41′′5 | 36 | 0.08 | 7.6 | 0.1 |
| SMC0070 | 0°51\,m26\,s15 | −73°16′59′′8 | 14 | 0.09 | 7.8 | 0.1 |
| SMC0071 | 0°51\,m31\,s78 | −73°09′38′′3 | 32 | 0.07 | 7.5 | 0.1 |
| SMC0072 | 0°51\,m41\,s09 | −73°13′46′′8 | 28 | 0.08 | 7.6 | 0.2 |
| SMC0074 | 0°53\,m14\,s03 | −72°50′25′′1 | 42 | 0.11 | 8.2 | 0.2 |
| SMC0075 | 0°51\,m52\,s91 | −72°57′13′′9 | 42 | 0.09 | 8.1 | 0.1 |
| SMC0076 | 0°51\,m54\,s32 | −73°05′52′′9 | 15 | 0.07 | 8.4 | 0.1 |
| SMC0077 | 0°52\,m12\,s47 | −72°31′51′′2 | 29 | 0.07 | 7.4 | 0.3 |
| SMC0078 | 0°52\,m13\,s34 | −73°00′12′′2 | 18 | 0.08 | 7.9 | 0.2 |
| SMC0081 | 0°52\,m33\,s65 | −73°01′04′′0 | 36 | 0.08 | 7.9 | 0.1 |
| SMC0082 | 0°52\,m42\,s12 | −72°55′31′′6 | 36 | 0.10 | 7.8 | 0.3 |
| SMC0083 | 0°52\,m42\,s27 | −72°58′47′′8 | 29 | 0.09 | 7.8 | 0.2 |
| SMC0087 | 0°52\,m48\,s99 | −73°24′43′′3 | 22 | 0.10 | 8.7 | 0.1 |
| SMC0089 | 0°53\,m05\,s28 | −72°37′27′′8 | 118 | 0.09 | 7.3 | 0.4 |
| Name         | OGLE-CL- | α_{2000} | δ_{2000} | Radius ["] | E(B-V) | log t | σ_{log t} |
|--------------|----------|----------|----------|-------------|--------|-------|----------|
| SMC0090      |          | 0°53'05"59 | -7°32'49"4 | 38 | 0.11 | 8.5 | 0.1 |
| SMC0092      |          | 0°53'17"90 | -7°45'59"5 | 34 | 0.12 | 7.4 | 0.1 |
| SMC0098      |          | 0°54'46"73 | -7°31'24"5 | 36 | 0.07 | 8.0 | 0.1 |
| SMC0099      |          | 0°54'48"24 | -7°27'57"8 | 36 | 0.08 | 7.6 | 0.2 |
| SMC0104      |          | 0°55'32"98 | -7°49'58"1 | 37 | 0.12 | 8.6 | 0.1 |
| SMC0105      |          | 0°55'42"99 | -7°52'48"4 | 44 | 0.11 | 8.0 | 0.1 |
| SMC0107      |          | 0°56'18"68 | -7°27'30"4 | 57 | 0.10 | 7.5 | 0.1 |
| SMC0109      |          | 0°57'29"80 | -7°15'51"9 | 24 | 0.04 | 7.7 | 0.1 |
| SMC0112      |          | 0°57'57"14 | -7°26'42"0 | 29 | 0.11 | 7.5 | 0.3 |
| SMC0115      |          | 0°58'33"64 | -7°16'51"6 | 15 | 0.07 | 7.3 | 0.3 |
| SMC0117      |          | 0°59'13"86 | -7°36'29"3 | 45 | 0.13 | 8.3 | 0.1 |
| SMC0118      |          | 0°59'48"03 | -7°29'02"5 | 41 | 0.08 | 8.2 | 0.1 |
| SMC0120      |           | 1°00'01"33 | -7°22'08"7 | 27 | 0.07 | 7.7 | 0.2 |
| SMC0121      |           | 1°00'13"03 | -7°27'43"8 | 30 | 0.08 | 7.9 | 0.1 |
| SMC0122      |           | 1°00'26"77 | -7°05'11"6 | 36 | 0.06 | 8.3 | 0.1 |
| SMC0124      |           | 1°00'34"41 | -7°21'55"8 | 34 | 0.06 | 7.6 | 0.1 |
| SMC0126      |           | 1°01'02"01 | -7°45'05"2 | 40 | 0.07 | 8.0 | 0.1 |
| SMC0128      |           | 1°01'37"15 | -7°24'24"7 | 36 | 0.09 | 7.1 | 0.3 |
| SMC0129      |           | 1°01'45"08 | -7°33'51"8 | 29 | 0.09 | 7.3 | 0.1 |
| SMC0134      |           | 1°03'11"52 | -7°16'21"0 | 28 | 0.05 | 7.8 | 0.1 |
| SMC0137      |           | 1°03'22"67 | -7°39'05"6 | 36 | 0.06 | 7.6 | 0.2 |
| SMC0138      |           | 1°03'59"02 | -7°00'10"5 | 18 | 0.04 | 7.4 | 0.4 |
| SMC0139      |           | 1°03'53"44 | -7°49'34"2 | 20 | 0.07 | 7.5 | 0.1 |
| SMC0140      |           | 1°04'14"10 | -7°38'49"1 | 25 | 0.09 | 7.2 | 0.3 |
| SMC0141      |           | 1°04'30"18 | -7°37'09"4 | 35 | 0.09 | 8.2 | 0.2 |
| SMC0142      |           | 1°04'36"21 | -7°09'38"5 | 41 | 0.06 | 7.3 | 0.1 |
| SMC0143      |           | 1°04'39"61 | -7°32'59"7 | 27 | 0.09 | 8.2 | 0.2 |
| SMC0144      |           | 1°04'05"23 | -7°07'14"6 | 18 | 0.05 | 7.6 | 0.2 |
| SMC0145      |           | 1°05'04"30 | -7°59'24"8 | 18 | 0.07 | 7.9 | 0.2 |
| SMC0146      |           | 1°05'13"40 | -7°59'41"8 | 14 | 0.06 | 7.3 | 0.3 |
| SMC0147      |           | 1°05'07"95 | -7°59'45"1 | 22 | 0.06 | 7.1 | 0.3 |
| SMC0149      |           | 1°05'21"51 | -7°02'34"7 | 36 | 0.08 | 8.2 | 0.1 |
| SMC0151      |           | 1°06'12"62 | -7°47'38"7 | 36 | 0.10 | 8.1 | 0.1 |
| SMC0153      |           | 1°06'47"74 | -7°16'24"5 | 27 | 0.04 | 7.2 | 0.3 |
| SMC0154      |           | 1°07'02"27 | -7°37'18"2 | 33 | 0.12 | 8.2 | 0.2 |
| SMC0155      |           | 1°07'27"83 | -7°29'35"5 | 41 | 0.09 | 7.7 | 0.2 |
| SMC0156      |           | 1°07'28"47 | -7°46'09"5 | 41 | 0.09 | 8.2 | 0.1 |
| SMC0158      |           | 1°07'58"97 | -7°21'19"5 | 77 | 0.08 | >9 | – |
| SMC0159      |           | 1°08'19"45 | -7°53'02"5 | 102 | 0.04 | >9 | – |
| SMC0160      |           | 1°08'37"48 | -7°26'20"9 | 20 | 0.04 | 7.6 | 0.3 |
| SMC0177      |           | 0°44"55"05 | -7°31'02"7 | 9 | 0.08 | 7.9 | 0.2 |
| SMC0187      |           | 0°47"05"78 | -7°22'16"6 | 14 | 0.04 | 8.2 | 0.1 |
| SMC0194      |           | 0°49"05"58 | -7°21'09"8 | 12 | 0.07 | 7.9 | 0.1 |
| SMC0195      |           | 0°49"16"45 | -7°14'50"8 | 28 | 0.07 | 7.3 | 0.2 |
| SMC0197      |           | 0°50"03"82 | -7°23'02"9 | 24 | 0.08 | 8.4 | 0.1 |
| SMC0198      |           | 0°50"07"51 | -7°11'25"9 | 22 | 0.06 | 7.9 | 0.1 |
| SMC0200      |           | 0°50"38"98 | -7°58'43"6 | 11 | 0.06 | 8.0 | 0.1 |
| SMC0210      |           | 0°52"30"30 | -7°02'59"0 | 21 | 0.07 | 8.2 | 0.2 |
| SMC0229      |           | 0°58"38"08 | -7°14'04"4 | 20 | 0.05 | 7.9 | 0.1 |
| SMC0230      |           | 1°00"33"15 | -7°15'30"2 | 9 | 0.08 | 7.5 | 0.3 |
Fig. 2. CMDs with fitted isochrone for three clusters of different age.

Table 1.

Fig. 2 displays CMDs of three well populated clusters of different age: NGC 330, IC 1611 and NGC 294 with the best fit isochrone.

3.3 Age Distribution

Fig. 3 presents distribution of age of 93 clusters from the central regions of the SMC.

Fig. 3 indicates that the cluster formation rate was not uniform in the past. Most clusters are objects younger than $20 \times 10^7$ years. However, it should be stressed that the presented distribution does not reflect only the rate of formation of clusters. It is also affected by a process of dissolution of clusters and possible selection effects connected with detection of clusters and age determination.

Our sample of the SMC clusters with determined age becomes incomplete for objects older than $10^9$ years because of limit of photometry and crowded field surrounding clusters. Objects with the age smaller than $20 \times 10^7$ years have the turn-off point well above the limit of photometric data and selection effects associated with detection and age determination should be negligible.
Therefore, we can conclude that process of formation of clusters during the last $20 - 30 \cdot 10^7$ years in the central parts of the SMC was either very non-uniform or process of disintegration of clusters in this galaxy is very efficient.

If we include to our sample two remaining oldest clusters: NGC 416 and NGC 419, adopt their ages from Mighell et al. (1998) and then compare the age distribution of clusters with that obtained for the SMC by Hodge (1987) and Galaxy by Wielen (1971) we may notice an evident deficiency of older clusters. It may reflect the incompleteness of our catalog for clusters older than $10^9$ years. On the other hand the dynamics of cluster disintegration in the central parts of the SMC suggests smaller number of older clusters in the center of the SMC than in the outer parts of this galaxy. It would be then important to look for older clusters in the central part of the SMC with deeper range photometric data than presented in this paper to confirm whether deficiency of older clusters in the SMC center is real.
4 Summary

We present age determination for numerous group of star clusters from the center of the SMC. The age of each cluster from the sample was determined using the standard procedure of isochrone fitting. Young clusters are the most frequent objects in the investigated group. The age distribution may be explained by non-uniform rate of cluster formation in this galaxy and/or strong disintegration processes. Based on these data we cannot, however, conclude whether the old clusters in the center of the SMC are less frequent than in the outer parts of this galaxy or in the Galaxy.

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