RAA 2016 Vol. 16 No. 4, 61 (8pp) doi: 10.1088/1674–4527/16/4/061
http://www.raa-journal.org *http://iopscience.iop.org/raa*

Research in Astronomy and Astrophysics

Population I Cepheids and understanding star formation history of the Small Magellanic Cloud

Yogesh Chandra Joshi[1], Auro Prasad Mohanty[2] and Santosh Joshi[1]

[1] Aryabhatta Research Institute of Observational Sciences, Manora Peak, Nainital 263002, India; *yogesh@aries.res.in*
[2] National Institute of Technology, Rourkela 769008, India

Received 2015 August 23; accepted 2015 October 16

Abstract In this paper, we study the age and spatial distributions of Cepheids in the Small Magellanic Cloud (SMC) as a function of their ages using data from the OGLE III photometric catalogue. A period - age relation derived for Classical Cepheids in the Large Magellanic Cloud (LMC) has been used to find the ages of Cepheids. The age distribution of the SMC Classical Cepheids is found to have a peak at $\log(\mathrm{Age}) = 8.40 \pm 0.10$ which suggests that a major star formation event might have occurred in the SMC about 250 ± 50 Myr ago. It is believed that this star forming burst had been triggered by close interactions of the SMC with the LMC and/or the Milky Way. A comparison of the observed spatial distributions of the Cepheids and open star clusters has also been carried out to study the star formation scenario in the SMC.

Key words: stars: Cepheids — star type: Pop I (classical) — galaxies: SMC — methods: statistical

1 INTRODUCTION

The Small Magellanic Cloud (SMC) is the closest satellite galaxy to the Milky Way (MW) after the Large Magellanic Cloud (LMC) which is about 60 kpc away from us and can be seen in the Southern hemisphere. The SMC is proximal enough to provide us with an excellent opportunity to study its star formation history, thus helping us to know the epochs and activities that led to its formation. Star formation can be triggered by several mechanisms like a turbulent interstellar medium, self-induced gravitational collapse of the molecular cloud, tidal shocking, or cloud-cloud interactions (McKee & Ostriker 2007). In recent times, the distribution of stellar populations in the Magellanic Clouds (MCs) has been studied with a variety of objects, e.g. star clusters (Pietrzynski & Udalski 2000; Harris & Zaritsky 2009; Glatt et al. 2010), Cepheid variables (Alcock et al. 1999; Nikolaev et al. 2004; Joshi & Joshi 2014), RR Lyrae variables (Subramaniam & Subramanian 2009; Haschke et al. 2012; Wagner-Kaiser & Sarajedini 2013), red clump stars (Koerwer 2009; Subramanian & Subramaniam 2012), and HI observations (Stanimirović et al. 2004), among others. These studies imply that episodic star formation events have taken place in the MCs, most likely due to repeated interaction between the MCs and/or with the MW.

Population I Cepheids, also known as Classical Cepheids (CCs), have been widely used to reconstruct the history of star formation in the MCs because they are intrinsically bright, easily observable and ubiquitous. They are ideal objects to understand star formation activity in the past 30–600 Myr of galaxies as a typical life of the CCs lies in this epoch. The light curves of CCs pulsating in the fundamental mode have an asymmetric nature with a steep rise to their amplitudes but with a slower fall. However, their first-overtone counterparts are more symmetric with much smaller amplitudes and shorter periods. Cepheids, as discovered by Leavitt (1912), obey a period-luminosity relation. Their pulsation period, colour, mass and intrinsic luminosity are related to each other. This led to their immense uses in tracing young stellar populations and star forming regions in extragalactic systems (Elmegreen & Efremov 1996).

In the past, CCs have been employed to study the spatial structure of the MCs (Caldwell & Coulson 1986; Haschke et al. 2012; Joshi & Joshi 2014; Subramanian & Subramaniam 2015). In order to further understand the star formation history in the SMC, a study of the distribution of CCs with a larger sample of data has been carried out in the present paper. Here, we aim to improve the understanding of the age distribution of Cepheids in the SMC and present a spatial map of the star formation in this dwarf galaxy through the period, age and spatial distributions of the CCs.

The paper is organized as follows: in Section 2, we give information about the data used in the present analysis. The period, age and spatial distributions of Cepheids are discussed in Sections 3, 4 and 5, respectively. A comparison of the distribution of Cepheids with star clusters is made in Section 6. Our results are summarized in Section 7.

2 DATA

Highly precise and calibrated $V - I$ photometric data of about 6.2 million stars were obtained from 41 fields in the SMC during the third phase of the Optical Gravitational Lensing Experiment (OGLE) (Soszyński et al. 2010). The fields were observed between 2001 and 2008 in the survey covering about 14 square degrees in the sky using the 1.3-m Warsaw telescope at the Las Campanas Observatory, Chile. Udalski et al. (2008) contain the details of the reduction procedure, photometric calibration, and astrometric calibration. All photometric data of their survey including the variable stars are available to the astronomical community from the OGLE web archive[1]. An extensive catalogue of 4630 CCs containing 2626 fundamental mode (F), 1644 first-overtone (1O), 83 second-overtone (2O), 59 double-mode F/1O, 215 double-mode 1O/2O, and 3 triple-mode Cepheids are reported by Soszyński et al. (2010). The present work deals with a sample of 4270 CCs that include 2626 F and 1644 1O Cepheids taken from the above mentioned catalogue.

3 THE PERIOD DISTRIBUTION OF CEPHEIDS

The periods, P (in days), of F CCs are in the range of $-0.08 < \log P < 2.31$, while those of 1O CCs lie in $-0.60 < \log P < 0.65$. The distribution of pulsation periods of CCs is different in different galaxies (Joshi et al. 2010). It also has peaks at different positions in the period distribution for the different galaxies. The period distribution depends upon chemical composition and many other factors like initial mass function, structure of the galaxy and the time spent by the stars pulsating during their transit through the instability strip (Becker et al. 1977; Alcock et al. 1999; Joshi et al. 2003). We have drawn a period distribution of the SMC CCs available in our sample with a bin width of $\Delta \log P = 0.05$ and shown in the right panel of Figure 1. The individual period distributions of F and 1O CCs are shown in the left panel. As can be seen, there is a clear pattern in the distribution of CCs as a function of period. When we fit a Gaussian profile in the distribution, we obtain two peaks corresponding to these two classes of CCs that lie at $\log P = 0.25 \pm 0.01$ and $\log P = 0.11 \pm 0.01$, for F and 1O CCs, respectively.

When we plot the period distribution of both the F and 1O CCs taken together, the combined sample gives an overall peak at $\log P = 0.212 \pm 0.007$. It is quite evident that the Cepheids with longer periods are favoured over those with shorter periods. The period distribution for the SMC CCs deviates from the general pattern observed in the case of LMC CCs as has been given by Joshi & Joshi (2014). Unlike SMC, they found two peaks in the LMC when both the F and 1O CCs were combined together, a result similar to galaxies like M31 and the MW (Antonello et al. 2002; Macri 2004; Vilardell et al. 2007; Joshi et al. 2010). The absence of a bimodal distribution in the case of the SMC could be due to low metallicity of the SMC as chemical composition of the host galaxy may play a role, however small, in the period distribution of the Cepheids. A similar analysis done by Serrano (1983), Alcock et al. (1999) and Joshi et al. (2010) in different galaxies also found that the frequency-period distribution varies in shape and in the location of the peak among different galaxies and is a function of the chemical composition.

4 THE AGE DISTRIBUTION OF CEPHEIDS

There have been many successful attempts to derive empirical period - age (PA) relations for Galactic, LMC and M31 Cepheids. Efremov (1978) gave an empirical period-age relation using the Cepheids in the Local Group of galaxies. Magnier et al. (1997) derived a semi-empirical period-age relation using Cepheids in NGC 206 and superposed it on that of M31 to trace the age distribution in order to understand the star formation history in that region. Later, Efremov & Elmegreen (1998) and Efremov (2003) derived many PA relations considering different combinations of the 74 cluster Cepheids in 25 different open clusters in the LMC.

Joshi & Joshi (2014) made an attempt at improving the PA relation using the same sample of Cepheids given by Efremov (2003) but taking ages of the clusters from the more recent study of Pandey et al. (2010). They drew a linear least squares fit to the points by plotting the mean period versus the age of clusters on a logarithmic scale and derived the following relation

$$\log(\mathrm{Age}) = 8.60(\pm 0.07) - 0.77(\pm 0.08)\ \log P. \quad (1)$$

Based on the evolutionary and pulsation models covering a broad range of stellar masses and chemical compositions, Bono et al. (2005) derived a PA relation for the Cepheids with metallicity 0.004 as $\log(\mathrm{Age}) = 8.49 - 0.79 \log P$. This is similar to the relation given by Joshi & Joshi (2014). Bono et al. (2005) also presented period-age-colour (PAC) relations apart from PA relations for F and 1O CCs. They found that the metal content of a galaxy affects the PA and PAC relations, though mildly. Short period Cepheids, which happen to be old, present minor intrinsic dispersions. Thus their ages could be more accurately estimated by using separate PA and PAC relations for Cepheids pulsating in the two modes. We however used the relation given by Joshi & Joshi (2014) to determine the ages of the CCs in the SMC. The F Cepheids in our sample have age ranges from 6.5 Myr to 460.4 Myr while the 1O Cepheids are between 125.2 Myr and 1151.8 Myr old. The age distributions of both F and 1O Cepheids are shown in

[1] *http://ogle.astrouw.edu.pl/*

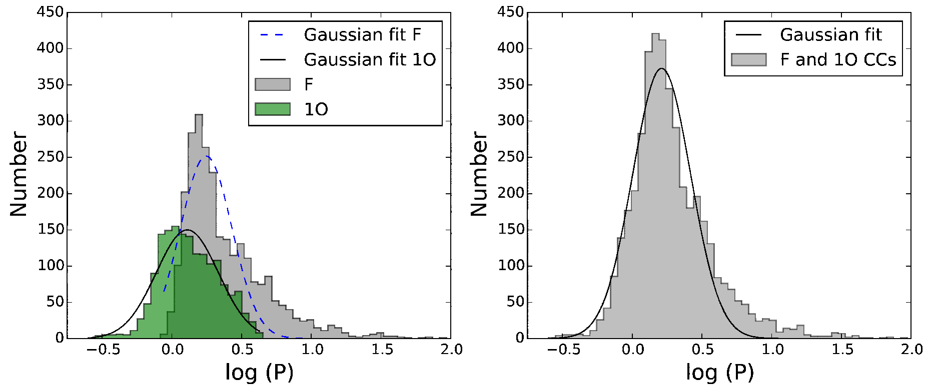

Fig. 1 The period distribution of CCs in the SMC. Left panel shows both F and 1O Cepheids separately while right panel shows their combined distribution. The dashed blue and solid black lines show the best fit Gaussian profiles.

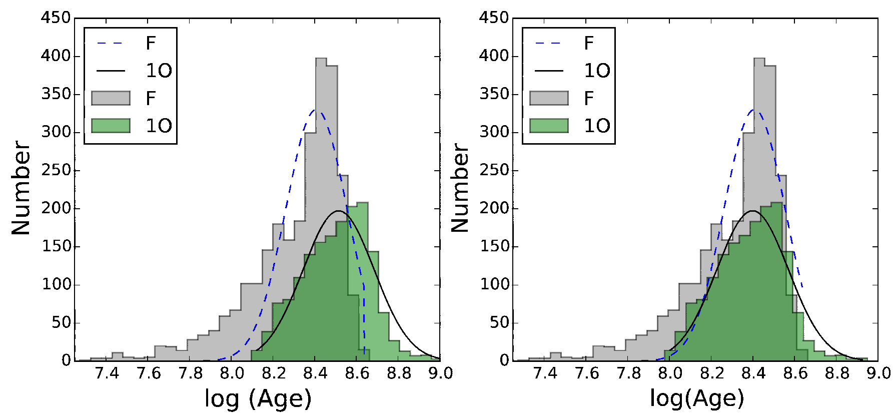

Fig. 2 Age distribution of CCs in the SMC. The age distribution is shown in the left panel for F and 1O Cepheids. In the right panel, the ages of 1O Cepheids are shown after the period conversion along with the F Cepheids. The dashed blue and solid black lines show the best fit Gaussian profiles.

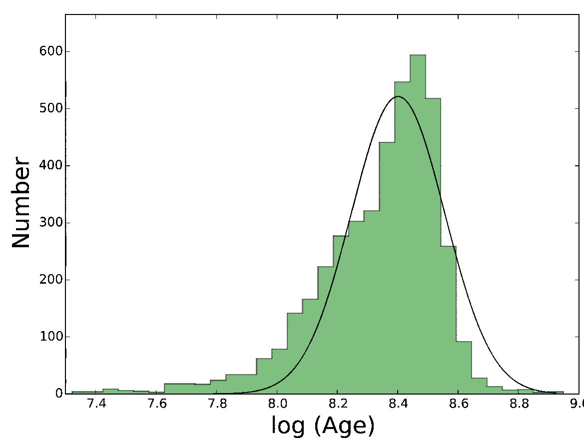

Fig. 3 Combined age distribution of CCs after using the PA relation and converting the periods of 1O Cepheids to the corresponding F Cepheids. The solid black line shows the best fit Gaussian profile.

the left panel of Figure 2. The age bin size in the distribution is $\Delta(\log(\mathrm{Age})) = 0.05$. We found two peaks occurring at $\log(\mathrm{Age}) = 8.41$ and $\log(\mathrm{Age}) = 8.52$ for F and 1O Cepheids, respectively.

A relation exists for transforming the periods of 1O Cepheids into the corresponding periods for the F Cepheids given by Alcock et al. (1995). This empirical linear relation is

$$P_1/P_0 = 0.733 - 0.034 \log P_1,$$

where P_0 and P_1 are periods of F and 1O Cepheids, respectively. However, Sziládi et al. (2007) recently provided a more accurate linear relation from the spectroscopic observations of the Cepheids which is given as follows:

$$P_1/P_0 = 0.710(\pm 0.001) - 0.014(\pm 0.003) \log P_0 \\ -0.027(\pm 0.004) \times [\mathrm{Fe/H}]. \quad (2)$$

This relation is used to transform the periods of 1O Cepheids to those of F Cepheids. Here, we note that there is only a weak dependence of [Fe/H] in the above conversion which can be ignored in the case of the SMC due to its extremely low metallicity. Following the above period conversion, the age distribution is drawn for F and 1O Cepheids separately in the right panel of Figure 2. The peak for 1O Cepheids is now shifted to $\log(\mathrm{Age}) \sim 8.40$. If we combined both sets of Cepheids after the period conversion, the overall peak of the age distribution occurs at $\log(\mathrm{Age}) = 8.40 \pm 0.01 \pm 0.09$ as shown in Figure 3. Here, the first error corresponds to the statistical error in the mean age estimation in the Gaussian fit and the second error represents the error due to uncertainty in the period-age relation. This suggests that there might be a major star formation event triggered in the SMC around 250 ± 50 Myr ago. When the two components of the MCs approach or recede, the star formation rate increases or decreases accordingly. Repeated tidal interaction between these two clouds thus leads to episodic star formation events in both the dwarf galaxies. However, such star formation events in the MCs can also be induced through stellar winds and supernova explosions through compression by turbulent motions (Larson 1993; Glatt et al. 2010).

5 THE SPATIAL DISTRIBUTION OF CEPHEIDS

To study the directional preference of star formation in the SMC during the epoch of triggered star formation events, we analyse the spatial distribution of CCs and their age distributions within the SMC. From the distribution of Cepheids in the RA-DEC plane as shown in the left panel of Figure 4, it can be seen that there is a huge concentration of Cepheids at the optical centre of the galaxy. In the right panels of the same figure, we draw similar distributions for Cepheids falling in the three different age intervals that are 200, 200–325 and > 325 Myr where F and 1O Cepheids are drawn with different colours. It is found that among all the F Cepheids, 36% fall in the youngest age group, 51% in the middle age group and the remaining 13% fall in the oldest age group. However, among all the 1O Cepheids, 30% fall in the youngest category, 47% in the middle age group and the remaining 23% are in the oldest group. Although they are nearly in the same fraction over those different age groups, it can be concluded that F Cepheids tend to be relatively younger.

The star formation scenario has been studied in the radial direction of the SMC. The frequency distribution is shown on the top panel in Figure 5. The RA-DEC plane is divided into 3600 (60×60) boxes. The distribution suggests that an explosion has triggered at the centre of the galaxy and stars are moving apart as the star forming event propagates. The age distribution shown at the bottom left panel and the dispersion in age of Cepheids shown at the bottom right panel further confirms this idea. There is a decrease in age along the diagonal towards the North-East which suggests that the star formation activity is propagating in this specified direction. There is less dispersion in ages on the border of the galaxy than towards the centre. This may suggest that star formation activities propagated from the centre to the outskirts of the galaxy.

Further, age distribution of Cepheids has been studied across the SMC by dividing them into four regions from West to East as shown in Figure 6. There is approximately an equal number of Cepheids in these regions. The shape of the distribution in each of the regions is different but the peaks are approximately at the same age. It is normally found that the peak in the age distribution shifts towards a larger value with the increase of metallicity. This suggests that there is zero metallicity gradient across the disk of the SMC. We can also clearly see that another peak emerges and gains significance as we proceed from West to East. This suggests that in those regions in the East, a separate star forming event might have occurred about 160 Myr ago (i.e. $\log(\mathrm{Age}) = 8.2$) apart from the one major star forming burst around 250 Myr ago as discussed earlier. Pietrzynski & Udalski (2000); Glatt et al. (2010) also found a peak at 160 Myr through the age distribution of star clusters in the SMC. The general profile based on the age distribution of the Cepheids matches well with that of star clusters in the SMC. From the analysis of CCs in the LMC, Joshi & Joshi (2014) have also noticed that there was a major star formation event triggered in the LMC about 125–200 Myr ago which was most likely triggered due to a close encounter between the SMC and the LMC. As this seems to be probably the same outburst which resulted simultaneously in both the dwarf galaxies due to an encounter between them, a combined analysis suggests that there was indeed a major star formation event that had happened in both the members of the MCs. According to models of Bekki & Chiba (2005), Kallivayalil et al. (2006), Besla et al. (2012), Diaz & Bekki (2012) and others, the last close encounters between the two components of the MCs happened about 100–300 Myr ago and they show that the MW, the LMC and the SMC interacted enough to produce the Magellanic stream between the clouds (Glatt et al. 2010).

6 SPATIAL DISTRIBUTION OF STAR CLUSTERS: A COMPARISON

It is quite interesting to make a comparison between the spatial distribution of star clusters and that of Cepheids as the PA relation uses the age of clusters and the periods of Cepheids in finding the ages of the Cepheids. Pietrzynski & Udalski (1999) plotted the age distribution of young clusters in the SMC and found two peaks at approximately

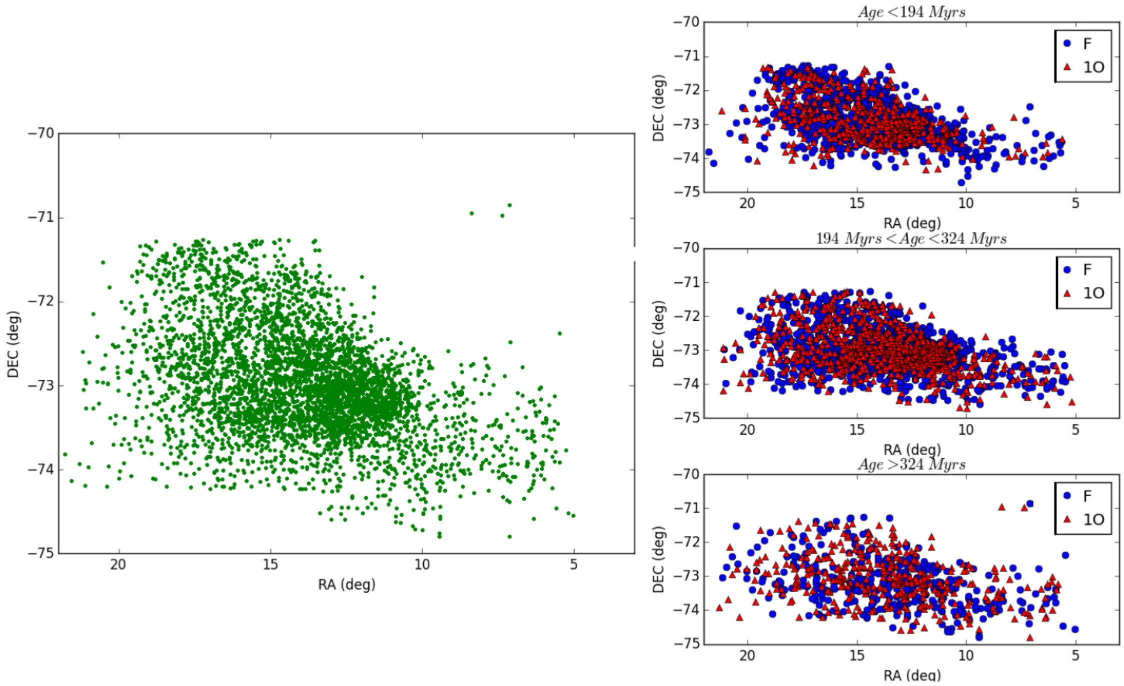

Fig. 4 Spatial distribution of the CCs in the SMC. In the right panel, the distributions of F and 1O Cepheids for three different age intervals are shown with blue dots and red triangles, respectively.

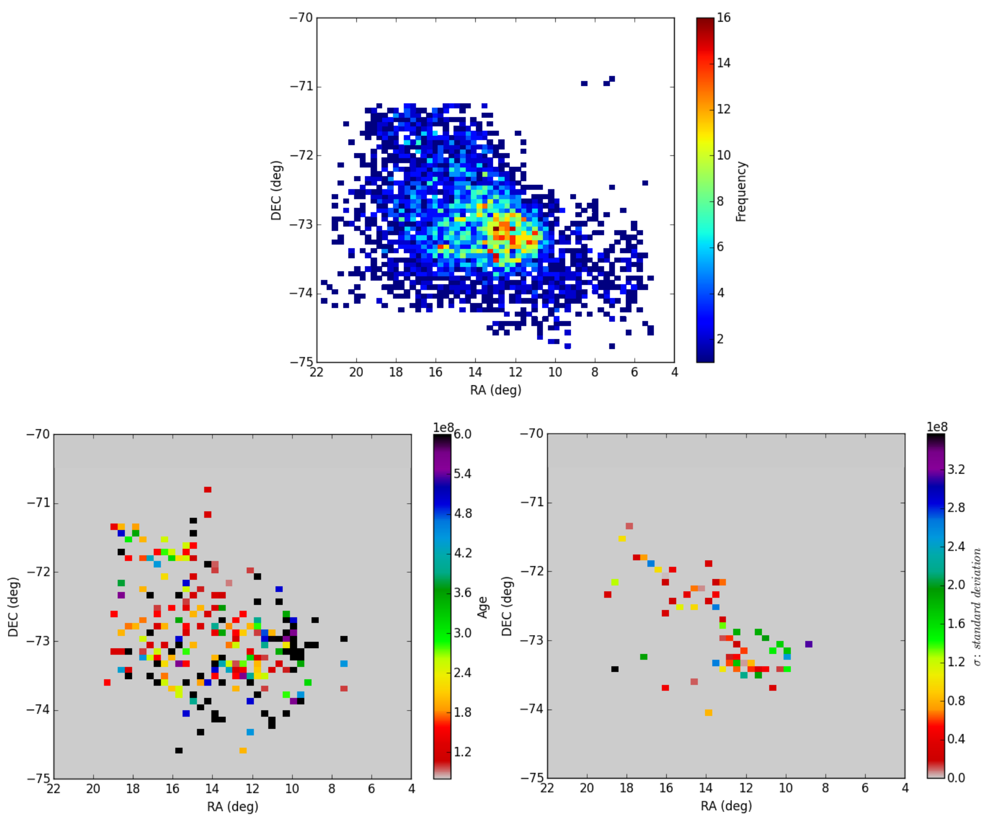

Fig. 5 Map of CCs in the SMC in the RA-DEC plane. Top panel shows the spatial distribution. In the bottom panel, age distribution is shown on the left while a distribution of standard deviations is shown on the right.

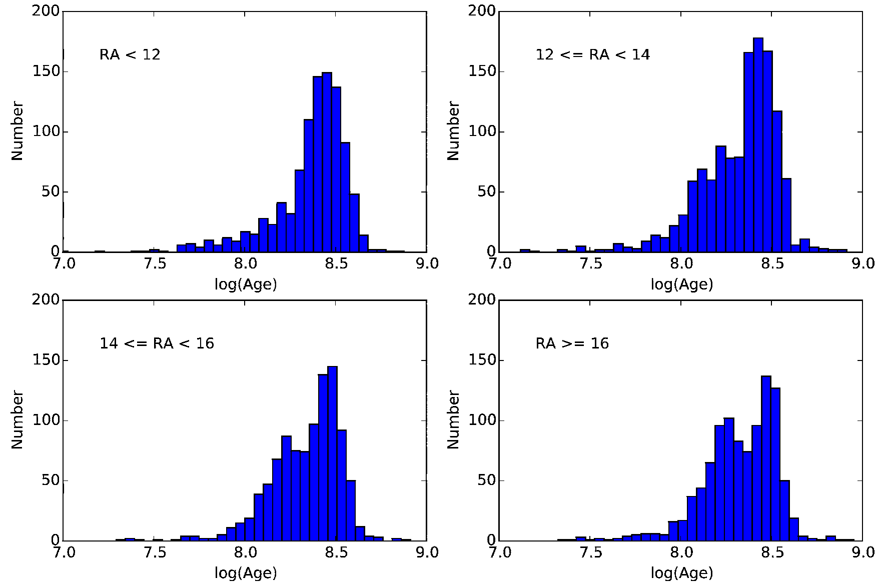

Fig. 6 Age distribution of the Cepheids in four different regions of RA (deg) in the SMC as marked on the top of each panel.

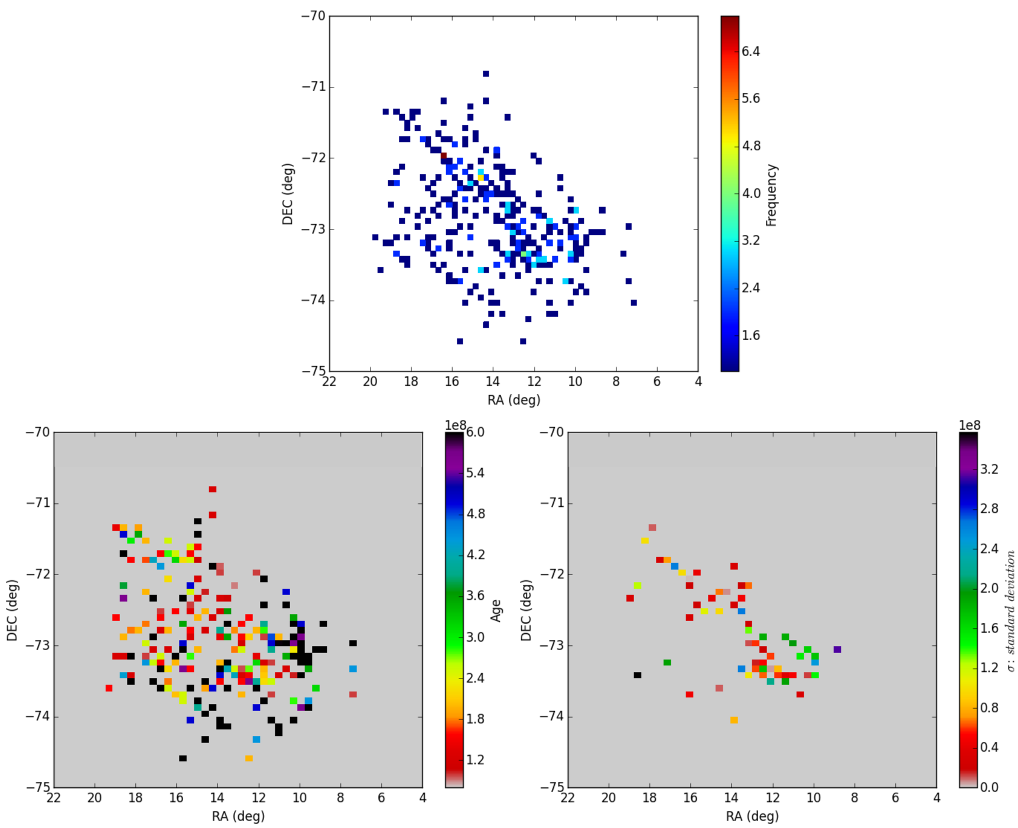

Fig. 7 Map of open clusters in the SMC in the RA-DEC plane. Top panel shows the spatial distribution. In the bottom panel, age distribution is shown on the left and a distribution of standard deviations is shown on the right.

100 Myr and 160 Myr. Glatt et al. (2010) also found a pronounced peak around 160 Myr for cluster formation in the SMC. From this, Subramanian & Subramaniam (2015) show that the age distribution of CCs and that of the clusters share a general profile.

Pietrzynski & Udalski (1999) gave the ages of 93 star clusters in the SMC. Glatt et al. (2010) found the ages of 324 star clusters in the SMC, although four of them are duplicate clusters having different ages. This was found out while comparing the celestial coordinates of all the clusters given by Pietrzynski & Udalski (1999) with those given by Glatt et al. (2010). Therefore, we considered the mean of the two given age values for each of these four clusters. The frequency distribution for the clusters is shown in the top panel of Figure 7. The clusters are seen to be distributed along the SMC bar in an elongated structure. The region was divided into 2500 small boxes across the length of RA and DEC. With the same box size, the average age of the clusters lying in each box was taken and an age distribution is plotted in the bottom left panel of Figure 7. The standard deviation of each box was also derived and the distribution is shown in the bottom right panel of Figure 7. It is seen from the frequency distribution of the clusters that their distribution is quite non-homogeneous and most of the clusters lie along the North-East South-West diagonal of the SMC with some spreading out of it. They seem to miss a circular region of half-a-degree radius on the East of the optical centre and they are scarcely populated around the boundaries. On comparing this distribution with the frequency distribution map of the Cepheids, it can be concluded that these star clusters tend to contain more of the younger stars. The age map of the clusters shows that older clusters lie in the South-West region while the sample becomes younger as we move towards the North-East. There is minimal dispersion in ages of the clusters towards the North-East than the other regions. Thus dispersion is found to be related to the propagating star forming event.

7 SUMMARY

Using the OGLE catalogue, we statistically analyse the star formation scenario in the SMC from very accurate period determinations of 2626 F and 1644 1O Cepheids detected in their third phase of observations. We have studied the period distribution of CCs and found a peak at $\log P = 0.212 \pm 0.007$. On plotting the period distributions of F and 1O Cepheids separately we yield peaks at $\log P = 0.25 \pm 0.01$ and $\log P = 0.11 \pm 0.01$, respectively. On combining these two classes of pulsating stars, after converting the periods of 1O Cepheids to those of F Cepheids and employing a period-age relation for the LMC, we found an age distribution comprising a pronounced peak at $\log(\mathrm{Age}) = 8.40 \pm 0.10$. A major star formation event might have triggered around 250 ± 50 Myr ago in the SMC followed by another such event in the Eastern region of the SMC about 160 Myr ago. A detailed study of different populations in the SMC (Pietrzynski & Udalski 2000; Stanimirović et al. 2004; Harris & Zaritsky 2009; Glatt et al. 2010; Subramanian & Subramaniam 2012; Haschke et al. 2012; Wagner-Kaiser & Sarajedini 2013; Joshi & Joshi 2014; Subramanian & Subramaniam 2015) as well as simulations by various groups (Bekki & Chiba 2005; Besla et al. 2012; Diaz & Bekki 2012) suggested that the last close encounters in the MCs happened around 100–300 Myr ago which has altered the star formation scenario in both the LMC and SMC. Hence our results for the SMC in the present paper are in broad agreement with these previous studies.

Our study shows that the Cepheids have a non-homogeneous distribution like a bursting balloon and are highly concentrated at the optical centre of this dwarf galaxy. It seems that the close encounters between the two components of the MCs and/or in between the MCs and the MW has induced episodic star formation in these galaxies. It suggests that the MCs are not in a bound system. In a comparison of spatial distribution of CCs and star clusters, a mutual correlation was noticed in the LMC, however, the number of known clusters in the SMC is still highly incomplete to make any firm conclusion.

Acknowledgements This publication makes use of data products from the OGLE archive. APM is thankful to the Indian Academy of Sciences (IASc), Bangalore for the financial assistance provided through the IAS-SRFP 2014. We also thank Brajesh Kumar and Ramkesh Yadav for their valuable inputs which have helped to improve this paper. YCJ acknowledges the grant received under the Indo-Russian project INT/RUS/RFBR/P-219 funded by Department of Science and Technology, New Delhi.

References

Alcock, C., Allsman, R. A., Axelrod, T. S., et al. 1995, AJ, 109, 1653
Alcock, C., Allsman, R. A., Alves, D. R., et al. 1999, AJ, 117, 920
Antonello, E., Fugazza, D., & Mantegazza, L. 2002, A&A, 388, 477
Becker, S. A., Iben, Jr., I., & Tuggle, R. S. 1977, ApJ, 218, 633
Bekki, K., & Chiba, M. 2005, MNRAS, 356, 680
Besla, G., Kallivayalil, N., Hernquist, L., et al. 2012, MNRAS, 421, 2109
Bono, G., Marconi, M., Cassisi, S., et al. 2005, ApJ, 621, 966
Caldwell, J. A. R., & Coulson, I. M. 1986, MNRAS, 218, 223
Diaz, J. D., & Bekki, K. 2012, ApJ, 750, 36
Efremov, I. N. 1978, Soviet Ast., 22, 161
Efremov, Y. N., & Elmegreen, B. G. 1998, MNRAS, 299, 588
Efremov, Y. N. 2003, Astronomy Reports, 47, 1000
Elmegreen, B. G., & Efremov, Y. N. 1996, ApJ, 466, 802
Glatt, K., Grebel, E. K., & Koch, A. 2010, A&A, 517, A50
Harris, J., & Zaritsky, D. 2009, AJ, 138, 1243
Haschke, R., Grebel, E. K., & Duffau, S. 2012, AJ, 144, 107
Joshi, Y. C., Pandey, A. K., Narasimha, D., Sagar, R., & Giraud-Héraud, Y. 2003, A&A, 402, 113
Joshi, Y. C., Narasimha, D., Pandey, A. K., & Sagar, R. 2010, A&A, 512, A66
Joshi, Y. C., & Joshi, S. 2014, New Astron., 28, 27
Kallivayalil, N., van der Marel, R. P., & Alcock, C. 2006, ApJ, 652, 1213
Koerwer, J. F. 2009, AJ, 138, 1

Larson, R. B. 1993, in Astronomical Society of the Pacific Conference Series, 48, The Globular Cluster-Galaxy Connection, eds. G. H. Smith, & J. P. Brodie, 675
Macri, L. M. 2004, in ASP Conf. Ser, 310, eds. D. W. Kurtz, & K. Pollard, 33
Magnier, E. A., Augusteijn, T., Prins, S., van Paradijs, J., & Lewin, W. H. G. 1997, A&AS, 126, 401
McKee, C. F., & Ostriker, E. C. 2007, ARA&A, 45, 565
Nikolaev, S., Drake, A. J., Keller, S. C., et al. 2004, ApJ, 601, 260
Pandey, A. K., Sandhu, T. S., Sagar, R., & Battinelli, P. 2010, MNRAS, 403, 1491
Pietrzynski, G., & Udalski, A. 1999, Acta Astronomica, 49, 157
Pietrzynski, G., & Udalski, A. 2000, Acta Astronomica, 50, 337
Serrano, A. 1983, Revista Mexicana de Astronomia y Astrofisica, 8, 131
Soszyński, I., Poleski, R., Udalski, A., et al. 2010, Acta Astronomica, 60, 17
Stanimirović, S., Staveley-Smith, L., & Jones, P. A. 2004, ApJ, 604, 176
Subramaniam, A., & Subramanian, S. 2009, A&A, 503, L9
Subramanian, S., & Subramaniam, A. 2012, ApJ, 744, 128
Subramanian, S., & Subramaniam, A. 2015, A&A, 573, A135
Sziládi, K., Vinkó, J., Poretti, E., Szabados, L., & Kun, M. 2007, A&A, 473, 579
Udalski, A., Szymanski, M. K., Soszynski, I., & Poleski, R. 2008, Acta Astronomica, 58, 69
Vilardell, F., Jordi, C., & Ribas, I. 2007, A&A, 473, 847
Wagner-Kaiser, R., & Sarajedini, A. 2013, MNRAS, 431, 1565