STAR FORMATION

Peeping into recent star-formation history of Magellanic Clouds

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Abstract. We study the distribution of fundamental-mode Cepheids in the Magellanic Clouds as a function of their positions and ages using the data from the OGLE IV survey. The ages of the Cepheids are determined through well known period–age relations for the LMC and SMC Cepheids, which are used to understand the star-formation scenario in the Magellanic Clouds. The age distributions of the Cepheids in LMC and SMC show prominent peaks around 158^{+46}_{-35} Myr and 219^{+63}_{-49} Myr, respectively. This indicates that a major star-formation event took place in the Magellanic Clouds about 200 Myr ago. It is believed that this episode of enhanced star formation might have been triggered by a close encounter between the two components of the Magellanic Clouds or due to a possible tidal interaction between the Magellanic Clouds and Milky Way galaxy during one of its pericentric passages around the Milky Way. Cepheids are found to be asymmetrically distributed in both the LMC and SMC in an elongated manner. A high spatial density clumpy structure is found to be located towards the eastern side of the LMC and the south-west direction of the SMC from their respective galactic centers.

Keywords. Star: Cepheids—star: classical—galaxies: LMC and SMC—method: statistical.

1. Introduction

Magellanic Clouds are among one of the most studied galaxy in the Universe due to their close proximity, favorable viewing angle and star-formation activities (Hilditch *et al.* 2005; Keller & Wood 2006). 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 (e.g., Diaz & Bekki 2012; Muraveva *et al.* 2018; Zivick *et al.* 2019). In recent times, the star-formation activity in Magellanic Clouds has been studied through scanning of various stellar populations, e.g., star clusters (Glatt *et al.* 2010; Piatti 2022), Cepheid variables (Subramanian & Subramaniam 2015; Jacyszyn-Dobrzeniecka *et al.* 2016; Joshi & Panchal 2019), RR Lyrae variables (Subramaniam & Subramanian 2009; Wagner-Kaiser & Sarajedini 2013; Cusano *et al.* 2021; Ripepi *et al.* 2022), red clump stars (Koerwer 2009; Subramanian & Subramaniam 2013; Skowron *et al.* 2021), among others. These studies unanimously imply that the episodic star-formation events have taken place in the Magellanic Clouds, most likely due to repeated interaction between the two components of the Magellanic Clouds and/or between the Magellanic Clouds and Milky Way Galaxy (Glatt *et al.* 2010; Indu & Subramaniam 2011; Meschin *et al.* 2014; Rezaeikh *et al.* 2014; Joshi *et al.* 2016; Rubele *et al.* 2018; Joshi & Panchal 2019).

Classical Cepheids have widely been used to probe the history of star formation in the Magellanic Clouds because these sources are intrinsically bright, easily observable and ubiquitous in both Large Magellanic Clouds (LMC) and Small Magellanic Clouds (SMC) (Jacyszyn-Dobrzeniecka *et al.* 2016; Deb *et al.* 2019). The use of classical Cepheids as tracers of young stellar populations comes from the fact that they obey the period–luminosity and period–age relations (Efremov & Elmegreen 1998; Bono *et al.* 2005; Joshi & Joshi 2014). They are thus ideal objects to understand the star-formation activity in the past 30–600 Myr of the galaxies

as typical life of the classical Cepheids spans in this age range. This led to their immense uses in tracing young stellar populations and star-forming regions in the extragalactic systems (Elmegreen & Efremov 1996).

In recent times, Optical Gravitational Lensing Experiment (OGLE) survey[1] has revolutionized the field by producing thousands of Cepheid light curves and derived parameters like periods, magnitudes, and amplitudes (Soszyński *et al.* 2017). In this paper, we aim to understand the age distributions of the Cepheids in the LMC and SMC to probe the star-formation history of the Magellanic Clouds. The paper is organized as follows: details of the data are given in Section 2. The period and age relations are discussed in Section 3. The age, spatial and spatio-temporal distributions of Cepheids in the LMC and SMC are studied in Sections 4 and 5. The detailed discussion of star formation in Magellanic Clouds is discussed in Section 6. We give summary of our work in Section 7.

2. Data

The OGLE survey provides photometric data in the *V*- and *I*-bands for stars in a 40 square degree region of the LMC using the 1.3-m Warsaw telescope at the Las Campanas Observatory, Chile (Soszyński *et al.* 2015, 2017). In the OGLE-IV survey, a catalog of 2476 fundamental-mode Cepheids in the LMC and 2753 fundamental-mode Cepheids in SMC are made available on their site, which are identified from their light curves and location in the period–luminosity diagram. The catalog contains coordinates of the Cepheids, their mean *V* and *I* magnitudes, amplitudes, periods and classification as well as cross-identification with other catalog. Although there are other higher-mode or multi-mode Cepheids reported in the OGLE survey, their reliable age estimation is rather difficult, unlike the fundamental-mode Cepheids. Unlike our earlier study in Joshi & Panchal (2019), where we used both fundamental-mode and first overtone Cepheids in the analysis, here, we have considered only fundamental-mode Cepheids in the LMC and SMC. This is to avoid the age estimation of the first overtone Cepheids through conversion of first overtone pulsation period to corresponding fundamental period by just supplying a single conversion factor, which may not be true for all the pulsating Cepheids. For all the fundamental-mode Cepheids (here onward we refer to fundamental-mode

Cepheids as Cepheids for simplicity), we also converted (RA, Dec) coordinates to corresponding (*X*, *Y*) coordinates using the relations given by Van De Kamp (1967).

3. Period–age relations

Ages of the Cepheids are used to understand the star-formation scenario in the Magellanic Clouds, however, there is no direct way of estimating the ages of Cepheids. The period–luminosity and mass–luminosity relations in classical Cepheids suggest that longer-period Cepheids have higher luminosities hence, more massive, which means these stellar populations are relatively younger in comparison to shorter-period Cepheids. This suggests that the period and age of Cepheids have an obvious connection. Since the period of a large number of Cepheids has been estimated with very high accuracy in the OGLE-IV survey having an error <0.001%, we used the period–age relations known for Cepheids in the LMC and SMC to determine their respective ages. To estimate the ages of Cepheids from their pulsation periods, many authors have provided semi-empirical relations in the past (Magnier *et al.* 1997; Efremov & Elmegreen 1998). In our previous study in Joshi & Joshi (2014), we used 74 LMC Cepheids found in 25 different open clusters to derive their period–age relation. For this purpose, we considered the mean period of Cepheids reported by Efremov (2003) and their corresponding cluster ages from Pandey *et al.* (2010) to draw an empirical period–age (PA) relation in the LMC for the Cepheids, which is given as:

$$\log(t) = 8.60(\pm 0.07) - 0.77(\pm 0.08)\log(P), \quad (1)$$

where age denoted by *t* is in years and *P* is the period given in days. For the SMC Cepheids, the following PA relation given by Bono *et al.* (2005) has been used to estimate the age of Cepheids:

$$\log(t) = 8.49(\pm 0.09) - 0.79(\pm 0.01)\log(P). \quad (2)$$

We used the above PA relations to determine the age of each Cepheid variable in the LMC and SMC. We found a typical average error of ∼40 Myr in the age estimations through these PA relations. Considering an insignificant age–metallicity gradient in the Magellanic Clouds (Piatti & Geisler 2013) in comparison to the error associated with the age estimation of the Cepheids, which are relatively younger populations, we have not taken into account any metallicity dependency in these relations.

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

4. Star-formation history in the large Magellanic Clouds

4.1 *Age distribution*

We estimated the age of each Cepheid in our sample of LMC Cepheids using Equation (1). The resulting age distribution of Cepheids is shown in Figure 1 for a bin width of $\Delta(\log(\text{Age})) = 0.05$. The standard deviation of the $\log(\text{Age})$ of all the Cepheids in a bin is used as x-axis error bar for that specific bin. Whereas there is only one Cepheid in the bin, the error bar represents the errors derived from Equation (1). The y-axis error bar for each bin corresponds to the poison noise of the number of Cepheids. The LMC age distribution rises gradually, but shows a steep fall. A single Gaussian fit as well as a double Gaussian fit are tested for this distribution. The single Gaussian fit to the distribution peaks at $\log(t/\text{yr}) = 8.16 \pm 0.10$ corresponding to an age of 145^{+37}_{-30} Myr. The double Gaussian fit shows
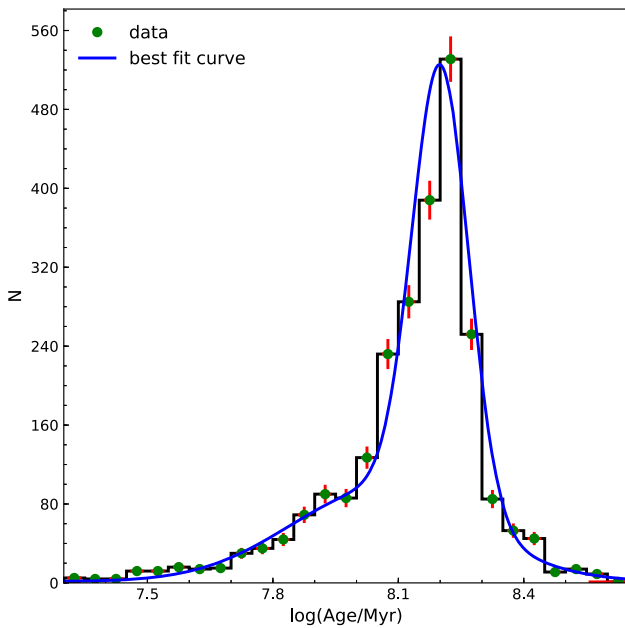

Figure 1. Age distribution of Cepheids in the LMC. The best-fit Gaussian profile is shown by a thick continuous line.

peaks at $\log(t/\text{yr}) = 8.06 \pm 0.11$ and 8.20 ± 0.11 corresponding to the ages of 115^{+33}_{-26} Myr and 158^{+46}_{-35} Myr, respectively. Though errors in the fitting coefficients are very small, but quoted uncertainty in the peak age represents a combined error, which arises from the errors on the coefficients in Equation (1) and statistical error in the Gaussian fit. We compared the observed distribution with fitted distribution using Kolmogorov–Smirnov (K–S) test for both single and double Gaussian fits. The K–S test statistics and *p*-values are listed in Table 1. A lower χ^2 and higher *p*-value from K–S test favors the double Gaussian trend of the LMC log(age) distribution. However, secondary peak in the age distribution of Cepheids in the LMC is not prominent enough to reveal any major star formation at this epoch.

4.2 *Spatial distribution*

In many previous studies, the distribution of Cepheids has been used to probe the structure of this dwarf cloud (e.g., Joshi & Joshi 2014; Inno *et al.* 2016). To study the spatial distribution of Cepheids in the LMC, we divided the whole sample of Cepheids into smaller segments with a dimension of 0.4×0.4 kpc square that results in a spatial resolution of ≈ 1.2 deg^2. The bin size was chosen to make an optimum number of segments without degrading much in the spatial resolution. Our selection resulted in 286 segments in the LMC. In Figure 2, we illustrate the heat map of the spatial distribution of Cepheids where color code represents the number density of Cepheids in each segment. A clumpy structure in the map is visible close to $(X, Y) = (-1.58, -1.18)$, which is towards the south-east direction from the known center of the LMC at $(X, Y) = (0, 0)$ that corresponds to $(\alpha, \delta) = (5^\text{h}19^\text{m}38^\text{s}, -69°27'5''.2)$, and shown by a plus sign in Figure 2. It is evident from Figure 2 that the center of LMC is not quite coincident with the dense region of the Cepheids which suggests that the enhanced star formation is not exactly taking place in the central part of the LMC.

Table 1. Results from single and double Gaussian fits for LMC and SMC log(age) distributions.

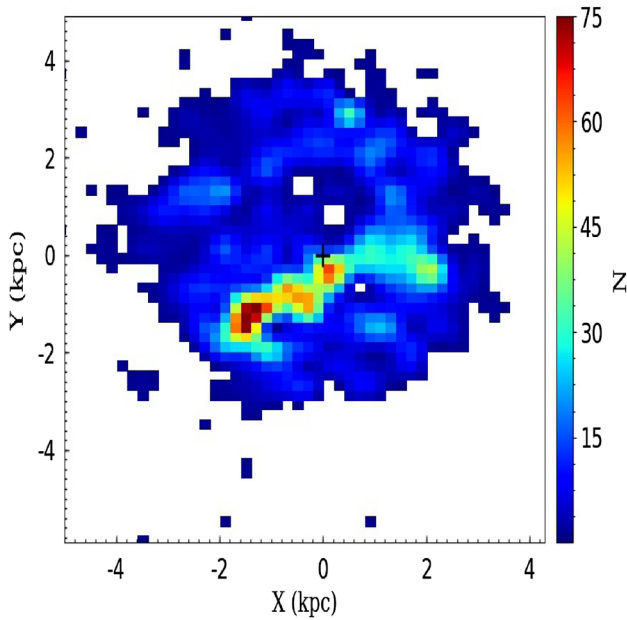| Galaxy	Gaussian	χ^2	K–S statistics	K–S *p*-value
LMC	Single	1114.94	0.3030	0.0772
LMC	Double	141.46	0.1515	0.8107
SMC	Single	2285.86	0.3250	0.0221
SMC	Double	223.02	0.1750	0.5313

Figure 2. Spatial heat map of the LMC, where color represents the number of Cepheids found in different segments. North is up and east is to the left. The position of the known center of the LMC is shown by a plus symbol.

We also noticed a bar-like elongated composition in the east–west direction of the LMC, which is conspicuous by the relatively larger density of Cepheids. The bar in the LMC is a well-observed structure in many previous studies inferred through different stellar populations including Cepheids (Deb *et al.* 2018; Joshi & Panchal 2019), RR Lyrae stars (Subramaniam & Subramanian 2009; Cusano *et al.* 2021; Ripepi *et al.* 2022), and Red clump stars (Subramanian & Subramaniam 2013; Skowron *et al.* 2021). Despite evidence of bar structure in the LMC, Cepheids are not uniformly distributed in the bar and there are few structures within the bar, where clumpy regions are more prominent, particularly, in the south-east region that is far off from the LMC center. This sort of patchy star formation within the bar has also been noticed by Mazzi *et al.* (2021). However, Monteagudo *et al.* (2018) ruled out any such significant spatial variations of the star formation across the LMC bar. A poor spatial density of Cepheids is also quite conspicuous in the northern arm of the LMC as evident in Figure 2.

4.3 *Spatio-temporal distribution*

To understand spatio-temporal distribution of Cepheids in 286 segments of the LMC, we illustrate the heat map of the spatial distribution of Cepheids as a function of their mean log (age) in Figure 3. Most of the Cepheids in the inner region have almost uniform age distribution,

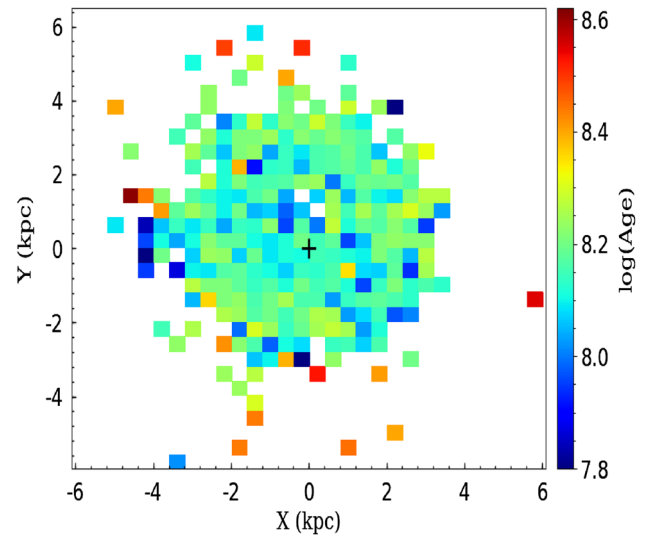**Figure 3.** Spatial distributions of the Cepheids in the 286 segments of the LMC as a function of their mean $\log(t/\mathrm{yr})$. North is up and east is to the left. The position of the known center of the LMC is shown by a plus symbol.

where mostly intermediate age Cepheids in addition to some young age Cepheids are seen. However, there is some sort of inhomogeneity towards peripheral regions, where many pockets of old-age Cepheids are observed. This gradual change in the age distribution of Cepheids from the inner region to the outer region suggests an outside-in quenching of star formation in the LMC disk. A similar structure in age gradient was also noticed by Meschin *et al.* (2014) in the LMC. It is believed that this stellar quenching may be resulted due to gas depletion at the time of star formation or ram-pressure stripping (Meschin *et al.* 2014). The outside-in quenching of star formation in the outer LMC disk is believed to be associated with the variation of the size of the HI disk as a consequence of gas depletion due to enhanced star formation or ram-pressure stripping, or the compression of gas disk as ram pressure from the Milky Way halo acted on the LMC interstellar medium (Meschin *et al.* 2014).

5. Star-formation history in small Magellanic Clouds

5.1 *Age distribution*

Like LMC, we also determined the age of each Cepheid variable in the SMC using the theoretical period–age relation given in Equation (2). The age distribution of Cepheids was examined in a logarithmic bin width of 0.04 dex and drawn in Figure 4, where a prominent peak
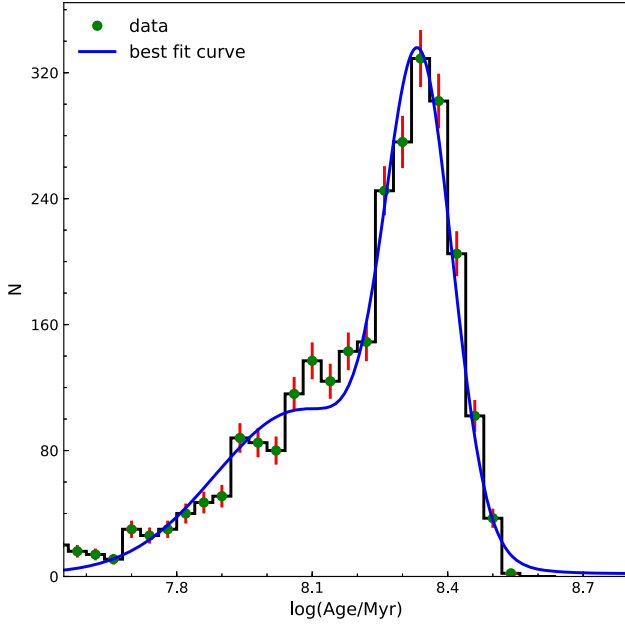
Figure 4. Age distribution of Cepheids in the SMC. The best-fit bi-modal Gaussian profile is drawn by a thick continuous line.

Figure 5. Same as Figure 2, but for the SMC.

is quite evident with some broad features toward left side of the peak. The error bars in Figure 4 are derived in a similar fashion as mentioned in Section 4.1. The distribution shows a slow increase in the age distribution followed by a sharp decrease toward older Cepheids, but the increase in age distribution is still sharper than LMC Cepheids age distribution. Similar to LMC, we tested both single and double Gaussian fits for SMC Cepheids $\log$ (age) distribution. The double Gaussian distribution peaks at $\log(t/\text{yr}) = 8.08 \pm 0.12$ and 8.34 ± 0.11. These two peaks correspond to 120^{+38}_{-29} and 219^{+63}_{-49} Myr with second peak as more prominent. The uncertainty in the peak age represents a combined error from the statistical error in the Gaussian fit and the errors in the coefficients in Equation (2). Both the χ^2 and K–S test statistics are mentioned in Table 1 and favors double Gaussian fits. Ripepi *et al.* (2017) also found a bi-modal distribution at 120 ± 10 and 220 ± 10 Myr with a promising peak at the later epoch.

5.2 *Spatial distribution*

To probe the star formation in the SMC during the epoch of the Cepheids evolutionary time scale, we analyse the spatial distribution of Cepheids within the SMC. For this purpose, we divided the SMC into 90×90 segments with a smaller dimension of 0.2×0.2 kpc square, obtaining a mean spatial resolution of ≈ 0.22 deg^2. A smaller size is chosen in the case of the SMC, because
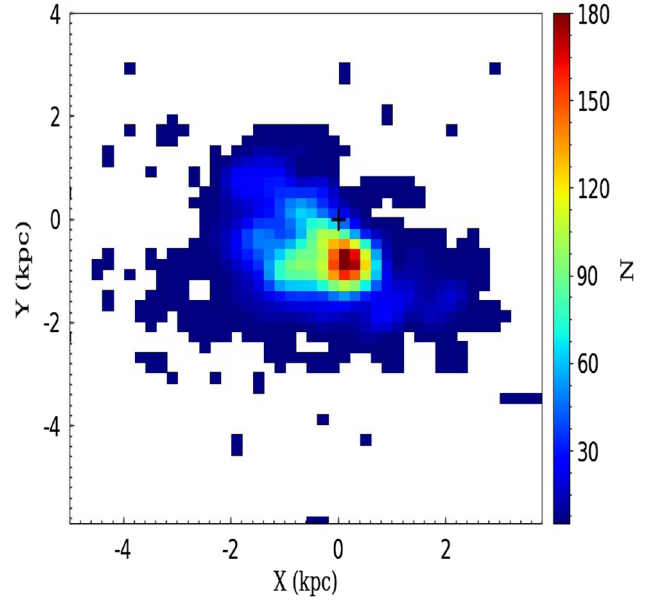
it contains a higher density of Cepheids per unit area in comparison to the LMC. We kept the same spatial cell size for all subsequent analyses of our study. We thus found 182 segments in the SMC. The total number of Cepheids was counted in each cell to construct the spatial map of Cepheid distribution. In Figure 5, we illustrate the spatial map of Cepheids in the SMC, where its known center at $(X, Y) = (0, 0)$ that correspond to $(\alpha, \delta) = (00^h 52^m 45^s, -72°49'43''.2)$, is marked by a plus symbol. The disk in the SMC is irregular and shows a complex geometric distribution as also noticed by Subramanian & Subramaniam (2015). The high-density region in the map lies in the vicinity of $(X, Y) = (0.02, -0.38)$, which is toward the west of the SMC center. Such an elongation in the SMC disk reveals its non-planar structure as also evident in the study of Ripepi *et al.* (2017) based on the study of 717 classical Cepheids from the VISTA near-infrared survey of the Magellanic Clouds.

5.3 *Spatio-temporal distribution*

In Figure 6, we draw the heat map of spatio-temporal distribution of SMC Cepheids in 182 chosen segments as discussed in Section 5.2. From the examination of spatio-temporal map of the SMC Cepheids, a complex and patchy age distribution is quite evident. The map shows a systematic distribution of intermediate-age Cepheids in the inner region of the SMC, while older clusters as well as a few isolated young clusters are distributed in small structures toward peripheral
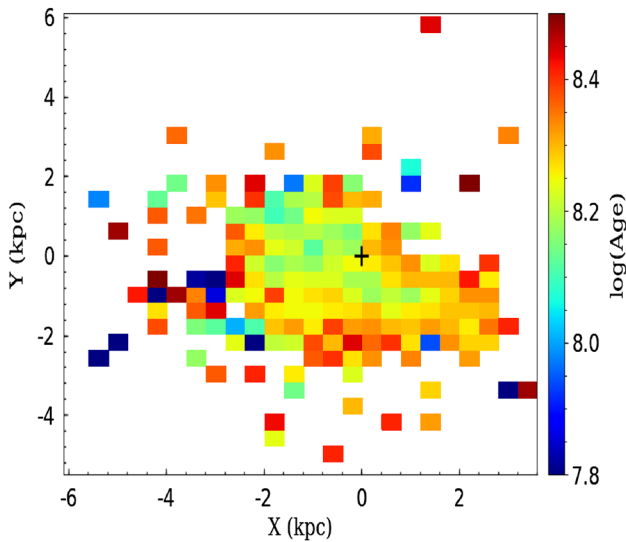
Figure 6. Same as Figure 3, but for the SMC.

regions. This suggests an inwards quenching of star formation in the SMC. Jacyszyn-Dobrzeniecka *et al.* (2016) and Ripepi *et al.* (2017) also found that young and old Cepheids have different geometric distributions in the SMC. They observed that closer Cepheids are preferentially distributed in the eastern regions of the SMC, which are off-centered in the direction of the LMC owing to tidal interaction between the two dwarf galaxies (Muraveva *et al.* 2018).

6. Discussion

The OGLE-IV survey data provided us an opportunity to statistically analyse the period and age distribution of Cepheids to probe the recent star formation scenario in the Magellanic Clouds. Taking advantage of a large and homogeneous sample of Cepheids from their precise period determination in the OGLE data, we studied the age distribution of these Cepheids from the previously reported period–age relations. The maxima in age distributions of Cepheids indicate a rapid enhancement of Cepheid formation at around 158^{+46}_{-35} Myr for the LMC and 219^{+63}_{-49} Myr for the SMC. Both the values are consistent within 1-σ. This suggests a rapid enhancement of Cepheids around 200 Myr ago in both the components of the Magellanic Clouds. This indicates a major star formation trigger at that epoch in the Magellanic Clouds. It is believed that a close encounter might have happened either between these two Magellanic Clouds components or their combined interactions with the Milky Way Galaxy that triggered an enhanced star-formation rate in these two dwarf clouds (Zivick

et al. 2019). As LMC and SMC are tidally locked, there are frequent interactions between these two components which lead to such episodic enhanced star formations in these cloud components.

It is believed that many star-formation episodes have had taken place in Magellanic Clouds at several epochs ranging from a few gigayears to a few million years ago (e.g., Harris & Zaritsky 2004; Rezaeikh *et al.* 2014; Rubele *et al.* 2018), which are often explained by the triggered mechanism due to close encounter between the two segments of the Magellanic Clouds. For example, models proposed by Kallivayalil *et al.* (2006); Besla *et al.* (2012); Diaz & Bekki (2012) and others suggest a close encounter between the SMC and LMC that has occurred around 100–300 Myr ago, resulting in triggered enhancement of the star-formation activity in both clouds. Using the open star clusters, Glatt *et al.* (2010) has studied the star-formation history in the Magellanic clouds and found various episodes of enhanced star formations at 800 Myr and 125 Myr ago, which is in accordance with the present study. The repeated tidal interactions between these two clouds thus, leads to the episodic star-formation events in both the dwarf galaxies and increase or decrease in star-formation rates depending upon whether these two Magellanic Clouds are approaching or receding (Joshi & Panchal 2019).

It is uncertain that the Magellanic Bridge and/or Magellanic Stream had formed due to such frequent interactions in the past between the two components of the Magellanic Clouds (Glatt *et al.* 2010; Diaz & Bekki 2012; Muraveva *et al.* 2018). As a result of these interactions, the tidal stripping of stars and gas from the gaseous disk took place in the Magellanic system. In fact, gas in the Magellanic Bridge is believed to have been largely stripped from the SMC as a result of such interactions (Dobbie *et al.* 2014; Mackey *et al.* 2017). Through the observations of the intermediate-age red clump stars using deep, near-infrared photometric data obtained with the VISTA Survey of the Magellanic Clouds (VMC), Subramanian *et al.* (2017) also found strong observational evidence of the formation of the Magellanic Bridge from tidally stripped material from the SMC.

7. Summary

In this work, we studied the spatial and age distribution of 2476 fundamental-mode Cepheids in the LMC and 2753 fundamental-mode Cepheids in the SMC reported by the OGLE-IV survey to understand the star-formation scenario in the Magellanic Clouds.

We explicitly used fundamental-mode Cepheids in our work as their age distribution can be well estimated through their robust period–age relations, while no such relations exist for higher-mode or multi-mode Cepheids. We grouped Cepheids in small segments in both the galaxies and considered 286 such segments in the LMC with a spatial resolution of 1.2 deg^2 and 182 segments in the SMC with a spatial resolution of 0.22 deg^2, where we found at least one fundamental-mode Cepheid. From the spatial distribution of Cepheids in both LMC and SMC, it was found that the Cepheids distribution is not planar, but significantly elongated. We noticed a relatively large density of Cepheids close to center of the SMC, however, the dense region of Cepheids is substantially shifted from its center in the LMC. The south-west side of the LMC disk is densely populated in comparison to the eastern side of its disk. We did not find any larger density towards the northern arm of the LMC, which shows a poor spatial density. In the case of SMC, a prominent dense clump of Cepheids was found toward the west of the SMC center. From the age distributions of Cepheids, we found an enhancement of Cepheids at around 158^{+46}_{-35} Myr in the LMC, while it is around 219^{+63}_{-49} Myr in case of SMC. The two peaks are close enough, which indicates an enhancement of Cepheid formation close to 200 Myrs ago in the Magellanic Clouds, which is believed to be due to cloud-cloud tidal interaction in the Magellanic Clouds or that between Magellanic Clouds and Milky Way galaxy during one of the pericentric passages of the Magellanic Clouds that orbits around the Milky Way.

The spatio-temporal distributions of Cepheids in the LMC and SMC suggested slightly preferential distribution where relatively older Cepheids were segregated towards the peripheral regions in both the LMC and SMC. Most of the younger Cepheids in the SMC are found to be located in the eastern part of the cloud suggesting that the eastern side of the galaxy may be relatively younger. As both components of the Magellanic Clouds have shown evidence of repeated star-formation episodes ranging from a few million years to a few giga years ago, it is essential to study Magellanic Clouds as a whole with a wide variety of stellar populations.

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