The updated statistics of binary star clusters in the Large Magellanic Cloud

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Abstract. Large Magellanic Cloud (LMC) has been known to host a significant fraction of binary star clusters whose dynamical and physical nature become interesting issue in accordance with the history of the galaxy. To understand the characteristics and the history of the binary clusters, it is important to establish a well-sampled statistics of this population. Among \( \sim 3100 \) star clusters (excluding associations), there are 634 clusters considered as binary/multiple cluster candidates. In this paper, the empirical statistics of the population, including spatial, size, separation, and age distribution are constructed using updated data. The current cluster compilation includes the ages of 88\% group components, which is three times more complete compared to the previous study. From the established statistics, we found an evidence that cloud fissions become the most probable mechanism of binary star cluster formation. Size and separation distribution of the clusters in binary/multiple systems show the importance of dynamical interaction within the systems.

1. Introduction

Large Magellanic Cloud (LMC) is recognized as the host of significant fraction of binary and multiple star clusters [1, 2, 3] whose dynamical and physical nature are interesting. The expected lifetime of this system is \( \lesssim 100 \) Myr since internal and external dynamics push the system to merger or separation ending [4, 5, 6]. Several formation mechanism have been proposed to explain the existing systems one of which is primordial binary cluster formation triggered by oblique collision of two molecular clouds [7, 8]. The latest collision between two Magellanic Clouds \( \sim 150 \) Myr ago increased the velocity dispersion within the galaxies and the probability of cloud-cloud collisions that produce binary and multiple star clusters. To confirm this scenario, well-sampled statistics of binary and multiple star clusters is needed.

Years ago, Dieball et al. [9] published a statistical study of binary and multiple clusters in the LMC as a continuing endeavour to understand the characteristics of this population. The statistics was based on the extended catalog containing 4089 clusters [10]. The study showed that more than half of detected pairs can not be considered as chance pairs. The binaries tend to be young (\( \lesssim 300 \) Myr) and have components with similar size and age. However, the study was unable to satisfactorily establish the cluster age distribution because of the lack of data.

In this study, we update the statistics of binary/multiple star cluster population in the LMC by exploiting the compiled star cluster properties from literature. The main objectives are to
establish the empirical distribution of binary/multiple cluster candidates in order to understand their characteristic and to investigate the history of this population in relation to the global history of the LMC. The data and method used in this study are presented in section 2 while the results are presented and discussed in section 3. The obtained conclusions are provided in section 4.

2. Data and Method
The main catalog used in this study comes from Bica et al. [11]. The catalog contains 9305 extended objects in Large Magellanic Cloud, Small Magellanic Cloud, and the interconnecting bridge. Among those objects, there are 3086 star clusters located in the LMC (excluding associations). For every object, Bica et al. [11] provide positions (\(\alpha, \delta\)), dimension (major and minor axis), and classification (e.g. C for clusters). The clusters’ equatorial coordinates were transformed into 2D cartesian system using Gnomon projection [12] centered on \((\alpha_0, \delta_0) = (80^\circ, -69^\circ45'):(\)

\[
x = -\frac{\cos \delta \sin (\alpha - \alpha_0)}{\sin \delta \sin \delta_0 + \cos \delta \cos \delta_0 \cos (\alpha - \alpha_0)},
\]

\[
y = \frac{\sin \delta \sin \delta_0 - \cos \delta \sin \delta_0 \cos (\alpha - \alpha_0)}{\sin \delta \sin \delta_0 + \cos \delta \cos \delta_0 \cos (\alpha - \alpha_0)}.
\]

From their positions in 2D space, cluster pairs were identified as two clusters with projected separation \(s < 20\) pc (\(< 1.37'\) assuming distance modulus of 18.49 [13]). Using this criterion, 281 binary and multiple systems were identified: 10 overlapped systems, 217 doubles, 39 triples, 9 quadruples, and 5 multiple systems with more than four components. This group list actually consists of 634 individual clusters.

The ages of the clusters were compiled from literature [14, 15, 16, 17, 18, 19, 20, 21, 22]. Various approaches were used in those literature, including SWB classification of young clusters, color-magnitude diagram fitting, and spectral energy distribution modeling. If any cluster has more than one published ages, then the arithmetic mean of those ages were adopted. However, the compiled cluster ages only cover 65% of the identified pairs/groups. To increase the completeness, a number of conspicuous clusters were re-analysed photometrically such that their ages could be estimated. The photometric data for these analysis came from the Optical Gravitational Lensing Experiment (OGLE, [23]) and the Magellanic Clouds Photometric Survey (MCPS, [24]) catalogue. PARSEC isochrones [25] were used to model the observed color-magnitude diagram of the clusters. This process increased the number of clusters with known age upto 88% (557) of the sample.

3. Results and Discussion
From the compiled list of clusters, both individual or the one that belongs to multiple systems, several empirical distribution were constructed as the platform of the analyses. Spatial distribution of the binary/multiple candidates is displayed in Figure 1, suplemented the age and average separation of the system. Group candidates tend to be located at the denser region of the LMC, confirming the results stated in [11] and [9]. Closer examination reveals no spatial clustering of the systems with specific projected separation. Both systems with small and large separation can be found in dense region or in the outer part of the LMC. It is noteworthy that systems with small separation and located outside the dense region have a higher probability to be considered as physical or real pairs.

On the other side, there is noticeable spatial clustering of age. Group candidates with \(\log t < 7.5\) can be found in 30 Doradus, constellation III, and the outer bar region (see Figure 1 for designations). The first two regions are considered as the most active star forming region.
Figure 1. Spatial distribution of the detected groups (circles) among the cataloged clusters in the LMC. Color code (available in the on-line version) in the left panel represents system age (log $t$), while the one in the right represents projected separation ($s$).

induced by the latest SMC-LMC collision about 200 Myr ago \[27\]. Most of the intermediate age systems ($7.5 \leq \text{log } t < 8.5$) can be found in the bar region, northwest arm, southeast arm, and blue arm. Almost all the systems in the SE arm have $8.0 \leq \text{log } t < 8.5$, in agreement with the increasing star formation history of this region at that time window \[26\]. The older groups (log $t \geq 8.5$) are more concentrated in the bar region. The existence of these groups cannot be explained by primordial formation. They are either statistical pairs or the products of tidal encounter.

The history of star cluster system in the LMC can also be examined from the age distribution ($dN/dt$) in Figure 2. The age distribution of single clusters was constructed using 1780 clusters with known age (58% of total sample), while the distribution of group components was constructed using 557 clusters (88% of total sample). The inverse ratio between the two can be considered as a proxy of binary fraction in the LMC over time. This fraction needs to be corrected from the selection bias (completeness) and observational bias (decontaminating chance pairs), but this correction is beyond the scope of this current study.

In general, the number of clusters decays with time as the clusters lose mass and dissolve to the field of stars. Abrupt increase of star formation rate at any epoch can be traced from the bumps at $t \approx 150$ Myr and $t \approx 1500$ Myr, in agreement with the finding of Baumgardt et al. \[28\]. The age distribution of group components is slightly different, particularly at the leftmost and the rightmost part. The excess of binary/multiple cluster candidates with very young ($\text{log } t \lesssim 7$) or higher binary fraction during the last 10 Myr supports the primordial formation and also the hierarchical cluster formation \[29\]. The binary fraction seems to be stable around 25% at 30–300 Myr, but there is pronounced increase of binary fraction at $t \approx 90$ Myr while the LMC-SMC collision assumed to occur at $t \approx 150$ Myr. This increase is a probable evidence of binary cluster formation triggered by cloud-cloud collision. The binary fraction fluctuates at the right-end of the plot as the number of old clusters decreases and the Poisson error grows.

Size distribution ($dN/dD$) is presented in Figure 3. For the clusters with diameter of $D \geq 10$ pc, the distribution can be approximated using power law $dN/dD \propto D^{-\eta}$. Size distribution
Figure 2. Bottom panel: age distribution of group components (filled circle) compared to the distribution of all clusters (with known age). Top panel: the binary fraction over time.

Figure 3. Size (diameter) distribution of group components (filled circle) compared to the distribution of all clusters. Power law $dN/dD \propto D^{-\eta}$ were fitted for $D \geq 10$ pc.

of individual clusters is well-fitted using $\eta = 4.0$, while the distributions of group components is fitted using $\eta = 3.6$. Shallower gradient for group components is caused by the excess of clusters with large diameter which is in accordance with the dynamical paradigm that binary and multiple clusters suffer mutual tide that heats and inflates the clusters [6].

The other interesting distribution is constructed from the projected separation of cluster pairs ($dN/ds$, see Figure 4). A trend of increasing $dN/ds$ is obvious as the number of chance pairs increases, e.g. $(dN/ds)_{\text{chance}} \propto s$. Dieball et al. [9] found multi-modal distribution of separation that peak at 6 and 15 pc, while this study found peaks at 6 and 12 pc. To emphasize the
bimodal nature of $dN/ds$, the empirical distribution was also calculated using Kernel Density Estimation (KDE). Dieball et al. argued that the dip of $dN/ds$ around 10 pc is caused by observational bias. However, three-dimensional separation distribution of cluster pairs in Milky Way also shows bimodality [30] though the observational bias is minimized. Dynamical evolution of binary star clusters can be involved in shaping bimodal distribution of separation. The dip between two peaks is the region where the inward gravitational force that leads to merger balances the outward force that disrupts the systems [5,6].

4. Conclusions

In this study, several empirical distribution of binary/multiple cluster candidates in the LMC have been constructed using the updated cluster data. From those empirical distributions, some conclusions can be drawn:

(i) Binary/multiple cluster candidates tend to be young and there is convincing evidence that the binary fraction increases as the rise of star formation rate. The last LMC-SMC collision at $t \approx 150$ Myr may be related to the increase of binary fraction at $t \approx 90$ Myr. This finding supports the theory of binary clusters formation induced by cloud-cloud collisions.

(ii) There is an excess of the number of group components with large diameter. Dynamical interaction between clusters in binary or groups may heat and inflate the clusters.

(iii) Distribution of cluster pairs separation has multiple peaks. Considering the similar result obtained for Milky Way binary cluster candidates, the observed bimodal distribution is thought as the product of dynamical evolution of the system, not merely observational bias.

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