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On a possible origin for the lack of old star clusters in the Small Magellanic Cloud

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ABSTRACT

We model the dynamical interaction between the Small and Large Magellanic Clouds and their corresponding stellar cluster populations. Our goal is to explore whether the lack of old clusters ($\gtrsim$7 Gyr) in the Small Magellanic Cloud (SMC) can be the result of the capture of clusters by the Large Magellanic Cloud (LMC) as well as their ejection due to the tidal interaction between the two galaxies. For this purpose, we perform a suite of numerical simulations probing a wide range of parameters for the orbit of the SMC about the LMC. We find that, for orbital eccentricities $e \geq 0.4$, approximately 15 per cent of the SMC clusters are captured by the LMC. In addition, another 20–50 per cent of its clusters are ejected into the intergalactic medium. In general, the clusters lost by the SMC are the less tightly bound cluster population. The final LMC cluster distribution shows a spatial segregation between clusters that originally belonged to the LMC and those that were captured from the SMC. Clusters that originally belonged to the SMC are more likely to be found in the outskirts of the LMC. Within this scenario, it is possible to interpret the difference observed between the star field and cluster SMC age–metallicity relationships for ages $\gtrsim$7 Gyr.

Key words: methods: numerical – galaxies: individual: SMC – Magellanic Clouds – galaxies: star clusters: general.

1 INTRODUCTION

Piatti & Geisler (2013) have claimed that the origin of the 15 known oldest Large Magellanic Cloud (LMC) clusters still remains unexplained and constitutes one of the most intriguing enigmas in our understanding of the LMC formation and evolution. In addition, they mentioned that the population of old Small Magellanic Cloud (SMC) clusters drastically decreases beyond ∼7 Gyr and there is only one older than 10 Gyr. Furthermore, based on the statistics of catalogued and studied clusters performed by Piatti (2011) and the latest identified relatively old SMC cluster (Piatti 2012), a total of only six relatively old clusters remain to be studied in this galaxy. From this result arises the possibility of connecting the origin of the oldest LMC cluster population to stripping events of ancient SMC star clusters. Indeed, it is curious in this context that the oldest SMC cluster is at the young and metal-rich extreme of the LMC globular cluster distribution.

Besla et al. (2012) have showed that the observed irregular morphology and internal kinematics of the Magellanic System (in gas and stars) are naturally explained by interactions between the LMC and SMC, rather than gravitational interactions with the Milky Way. They examined the gas and stellar kinematic centres of the LMC; the warped LMC old stellar disc and bar; the gaseous arms stripped out of the LMC by the SMC in the direction of the Magellanic Bridge; the stellar debris from the SMC seen in the LMC disc field; etc., to strongly reinforce the suspicions of de Vaucouleurs & Freeman (1972) that the interaction with the Milky Way is not responsible for the LMC's morphology. Moreover, these conclusions provide further support that the Magellanic Clouds (MCs) are completing their first infall to our Galaxy.

As far as MC's star clusters are considered, Bekki et al. (2004) proposed that differences in the birthplaces of both MCs and initial masses between the two caused the LMC cluster age gap and the lack of old SMC clusters. They suggested that the LMC/SMC were formed as different entities rather than as a binary protogalaxy in order to explain the difference in the MCs star cluster formation history. On the other hand, Piatti et al. (2002) suggested that the SMC was formed from the detachment of some part of the LMC

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containing gas and/or star clusters. Note that both works aimed at explaining the remarkably complementary age–metallicity relationship observed in the MCs.

In this Letter, we trace for the first time the MCs star cluster dynamical behaviour from numerical simulations in order to explore the possibility that SMC globulars have been stripped out by the LMC. In Section 2, we deal with the computation of the star cluster orbits, whereas in Section 3 we discuss the probability of cluster capture in terms of different scenarios and parameter values. In Section 4, we summarize our results.

2 NUMERICAL SIMULATIONS

In order to investigate whether the above-mentioned hypothesis may be true, we ran a series of numerical experiments. We chose 10^{10} M$_\odot$ as the unit of mass, 1 kpc as the unit of distance and the gravitational constant $G = 1$. This yields 4.7147 Myr as the unit of time and a unit of velocity equal to 207.4 km s^{-1}. The experiments consisted in following the evolution of the MCs in mutual gravitational interaction on bound orbits, plus 100 point masses around each cloud representing the clusters. The initial distance between both galaxies was 100 kpc.

We simulated the MCs through Hernquist potentials (Hernquist 1990):

$$\Phi(r) = -\frac{GM}{r+a}, \tag{1}$$

where M is the mass and a is the scalelength of the model. We used $M_{\rm L} = 1.8 \times 10^{11}$ M$_\odot$ and $a_{\rm L} = 21.4$ kpc for the LMC, and $M_{\rm S} = 2.1 \times 10^{10}$ M$_\odot$ and $a_{\rm S} = 7.3$ kpc for the SMC (Besla et al. 2012).

We wanted to generate initial conditions for the bounded binary orbits of the MCs with different eccentricities, in order to see whether exchanges of clusters may be possible in different scenarios. However, since the MCs are not point masses, a Keplerian eccentricity and its associated elliptic orbit are not defined. We therefore defined the eccentricity as

$$e = \frac{r_{\rm a} - r_{\rm p}}{r_{\rm a} + r_{\rm p}}, \tag{2}$$

where $r_{\rm a}$ and $r_{\rm p}$ are the pericentric and apocentric distances of the rosette orbit between the two spherical potentials, respectively. Then, to obtain an orbit of one galaxy about the other with a given e, we first integrated a test orbit with a chosen initial separation and with a guess on the initial velocity (perpendicular to the radius joining both MCs, i.e. we started at the apocentre of the orbit) and computed the resulting eccentricity. The initial separations considered were 60 and 100 kpc. By iterating this process, the initial velocity corresponding to the desired e was found. Finally, the initial positions and velocities of the MCs thus generated were translated to the centre of mass coordinate system.

We then distributed 100 clusters of mass 10^5 M$_\odot$ around each galaxy, with positions and velocities following the corresponding Hernquist distribution function with isotropic velocity dispersion (Hernquist 1990):

$$f(\boldsymbol{x}, \boldsymbol{v}) = \frac{M}{8\sqrt{2}\pi^3 a^3\, w^3}\,\frac{1}{(1-s^2)^{5/2}} \times \left[3 \arcsin s + s(1-s^2)^{1/2}(1-2s^2)(8s^4 - 8s^2 - 3)\right], \tag{3}$$

where $(\boldsymbol{x}, \boldsymbol{v})$ is a point of the phase space, $w = (GM/a)^{1/2}$, and $s = (-E)^{1/2}/w$, being $E = \frac{1}{2}v^2 + \Phi(r)$ the energy per unit mass of a cluster. In the last equation, we have used the usual notations $r = |\boldsymbol{x}|$ and $v = |\boldsymbol{v}|$. The density profile turns out to be:

$$\rho(r) = \frac{M}{2\pi}\frac{a}{r(r+a)^3}, \tag{4}$$

though we added a cut in this distribution at different fractions of the tidal radius, $R_{\rm t}$, of each galaxy (see details below). The tidal radius of the LMC (SMC) is 74 (26) kpc for an initial separation of 100 kpc, and 46 (15) kpc for an initial separation of 60 kpc. The considered cut to the initial cluster distributions are R_t, $0.5R_{\rm t}$ and, as a limiting case, a cut at 10 kpc for both galaxies. The initial radial extent of a galaxy's cluster population is still a matter of debate. Using numerical simulations, Bekki (2005) (see also Bekki & Yahagi 2006) finds that this extent can be approximated as a fraction of the half-mass radius of the host's dark matter halo. The half-mass radius, $R_{\rm h}$, of the MCs can be estimated as $R_{\rm h} = 0.6R_{200}$ (see Willman et al. 2004), where R_{200} corresponds to the virial radius of the halo. Considering $R_{200} = 117.1\,(57.1)$ kpc for the LMC (SMC) (Besla et al. 2012), we obtain an $R_{\rm h} = 70.3\,(34.3)$ kpc. These values are consistent with the tidal radii obtained when an initial separation of 100 kpc between the clouds is considered.

Since the MCs are fixed potentials, there is no dynamical friction in their orbits. To make the simulations more realistic, we added this acceleration to the velocities $\boldsymbol{v}$ of the MCs in their orbits by using Chandrasekhar's dynamical friction formula (Chandrasekhar 1943; Binney & Tremaine 2008):

$$\frac{{\rm d}\boldsymbol{v}_2}{{\rm d}t} = -4\pi G^2 M_2 \rho_1 \ln\Lambda \left[\int_0^{v_2} v^2 f_1(v)\,{\rm d}v\right]\frac{\boldsymbol{v}_2}{v_2^3}, \tag{5}$$

where the subindex 1 refers to the galaxy causing the friction, the subindex 2 refers to the galaxy being decelerated, $\boldsymbol{v}_2$ is the relative velocity of the MCs and Λ is the Coulomb factor defined in our case as

$$\Lambda = \frac{r v_2^2}{M_2(r)}, \tag{6}$$

where r is the distance between the MC's centres and $M_2(r)$ is the mass of the galaxy 2 enclosed into r. The distribution function of the velocities of the galaxy 1, $f_1(v)$, should be obtained from equation (3) by integrating to all positions. Unfortunately, there is no closed form for the primitive, so that the integral of equation (5) was approximated with

$$\int_0^{v_2} v^2 f_1(v)\,{\rm d}v \simeq \frac{1}{6}\left({\rm erf}(x) - \frac{2}{\sqrt{\pi}}{\rm e}^{-x^2}\right), \tag{7}$$

with $x = 2v_2\sqrt{a_1 M_1}$. This approximation gives an error of less than 6 per cent at any v_2.

We used a tree code (Barnes & Hut 1986; Hernquist 1987) to perform the experiments. But since we considered both MCs as two particles not being point masses, we modified the tree algorithm in order to self-consistently follow their evolutions. At each time step, we first started by assigning a null mass to both galaxies. This avoids the MCs being attracted to each other as Keplerian potentials, but allowing the 200 clusters to be gravitationally influenced one to each other and to accelerate their host galaxies. After computing all these accelerations, we put the two Hernquist spheres centred at the positions where the galaxies were found at that time, and added the accelerations produced by them on the clusters and on each other as well. The system was then evolved in time, and a new time step was taken.

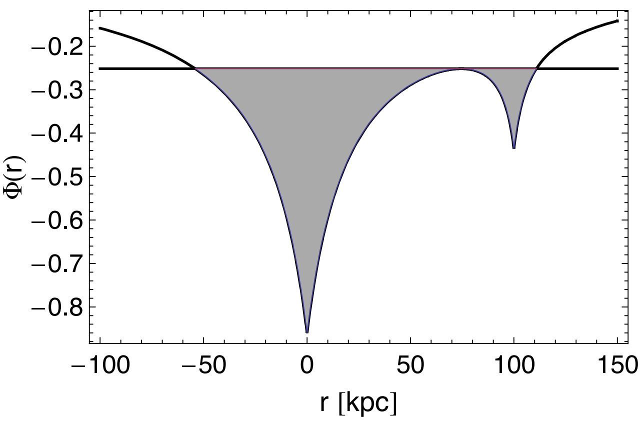

Figure 1. Example of the total potential of the MCs along the line joining their centres. The LMC and the SMC are here located at $r = 0$ and $r = 100$ kpc, respectively; the saddle point determining the respective tidal radii is at $r = 74.53$ kpc. The straight line shows the value of the potential Φ_0 at the saddle point; the grey areas correspond to the regions of influence of each galaxy, when the value of the equipotential Φ_0 is taken as a reference.

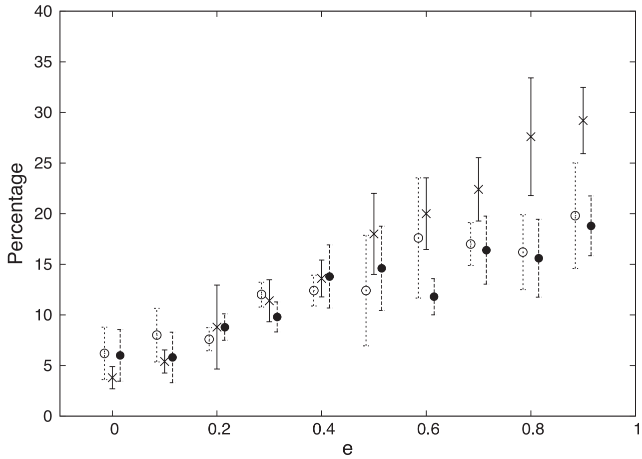

Figure 2. Percentage of clusters that initially belonged to the SMC and, at the time of the third apocentre, were captured by the LMC. Points and crosses refer to experiments without and with dynamical friction, respectively. The latter were slightly shifted to the right for a better readability. Also shown are the results of experiments with dynamical friction but with initial separation between the galaxies of only 60 kpc (open circles, slightly shifted to the left). The error bars correspond to the standard deviation computed from the five experiments done for each case.

3 RESULTS

For each chosen e value, we integrated five different realisations of the cluster distributions – using different seeds in each case – in order to be able to estimate the statistical uncertainties. During the execution of each experiment, we kept track of the membership of each cluster in order to detect any possible exchange between both galaxies. To this purpose, we first computed the position of the saddle point corresponding to the MCs, i.e. the point at which the acceleration due to both galaxies is zero, as exemplified in Fig. 1. This point, which lies on the line joining the centres of the MCs, approximately determines the instantaneous tidal radius of each galaxy. Note that this is an approximate value due to the fact that the equipotential corresponding to the saddle point is not spherical around the centres of the MCs.

Let the potential of this saddle point at any time t be $\Phi_0(t)$. We might now decide whether a given cluster belongs to one or another galaxy by comparing both its distance to the galaxy centres with the respective tidal radii, and its energy (per unit mass) relative to the galaxies with Φ_0. Fig. 1 shows in grey the regions of membership when this criterion is chosen. This procedure satisfactorily works when dealing with static potentials. However, in our case, it has a serious drawback: since $\Phi_0(t)$ depends on time, it could happen that some clusters have energies slightly below Φ_0 at a given time, and slightly above Φ_0 at the next time step, so that they are 'lost' due to the shifting of Φ_0 without their dynamical status having been significantly changed.

Since we are interested in real star cluster exchanges between the MCs, we considered a star cluster to belong to a galaxy whenever the former is located inside the tidal radius of the latter, irrespective of the energy. It might happen that a star cluster – which has acquired too much energy – be assigned to an MC, even though it might be unbounded from both MCs. However, in such a case, our bookkeeping would still result reasonable, since the star cluster will quickly escape and go beyond any tidal radii.

We ran each experiment until the apocentre following the third pericentre of the orbit is reached; longer times might imply the fusion of the galaxies or the tidal disruption of the SMC (Besla et al. 2012). For each experiment, we logged the MC to which every cluster initially belonged to and, at the final time of integration, we recomputed the membership as described above. Fig. 2 shows the percentage of clusters that initially belonged to the SMC and, at the time of the third apocentre, were captured by the LMC. For these experiments we considered a cut to the initial radial extent of the cluster population equal to R_t. We present the results both with (filled circles) and without (crosses) dynamical friction. As can be seen, when the dynamical friction is taken into account there are far less captures than in the other case, especially at large eccentricities, notwithstanding the closer pericentres of the former case. This may be explained by the fact that the closer a pericentre, the smaller the time of high interaction, so the MCs interact more strongly but during a shorter period of time when the dynamical friction is present. In any case, captures appear to be a frequent, non-negligible feature of the interaction between the MCs. Fig. 2 also shows the outcome of an additional experiment including dynamical friction, but with the galaxies initially separated 60 kpc instead of 100 kpc (open circles). It is clearly seen that this parameter does not play any important role in the rate of captures. In general, when dynamical friction is taken into account, approximately 15 per cent of the SMC clusters are captured by the LMC, for $e \geq 0.4$.

Fig. 3 shows, for the case $e = 0.7$ with dynamical friction, the original distribution of energies of the SMC's clusters (we have averaged the values of the five experiments in order to reduce the noise). Each bin is subdivided into three parts, depending on the fate of the clusters. Those captured by the LMC correspond to the lower parts, limited by dashed lines (blue online); those which were left unbounded from both galaxies are piled above the latter, limited by thick lines (red online), and those which remained bounded to the SMC are represented by the upper parts, piled on top. As can be seen, the energy region from which the clusters are stripped out from the SMC correspond to those less bounded, i.e. those farther out from the galaxy. Also, we may expect the intergalactic medium to be filled with clusters lost from the SMC. Approximately 50 per cent of its clusters are ejected. The experiments done with other eccentricities showed the same trend.

It might be suspected that our choice of initial conditions favours the loss of clusters since, even though they are spatially located inside their respective galactic tidal radii at the beginning of the

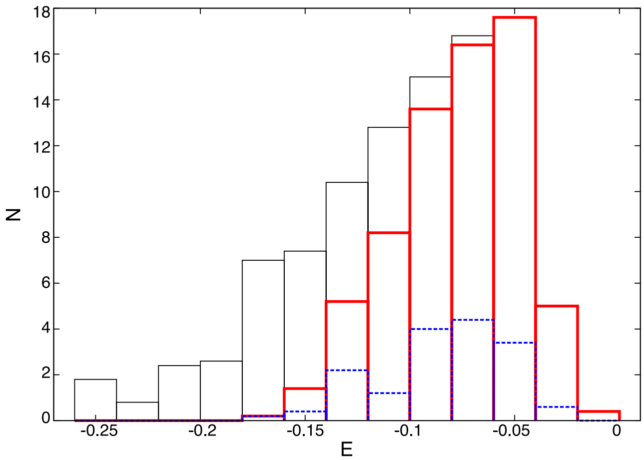

Figure 3. Distribution of initial binding energies of the SMC's clusters, for the case $e = 0.7$ and with dynamical friction, averaged over the five experiments. For each bin, the clusters captured by the LMC (lower areas), those unbounded at the end of the experiment (middle areas), and those that remained bounded to the SMC (upper areas) are also shown. The bins correspond to spherical shells of constant width.

integrations, some of them have energies above the saddle point between the MCs. However, this should not be a big concern since previous tidal interactions with other galaxies, or even the Milky Way, are expected to expand the original cluster radial distribution, leaving some clusters on high-energy orbits (Muzzio 1986).

Nevertheless, we ran an additional set of experiments, considering dynamical friction, with all the clusters initially placed inside the tidal radii *and* having energies below the threshold of the saddle point. Note that this condition imposes a more centrally concentrated radial distribution of clusters than before. In what follows, the initial eccentricity of the SMC's orbit about the LMC is fixed at $e = 0.7$, as this is the preferred eccentricity in the models presented by Besla et al. (2012). The experiments yielded 14 ± 3 per cent of captures of SMC's clusters by the LMC, whereas 20 ± 7 and 20 ± 6 per cent of LMC's and SMC's clusters were thrown into the intergalactic medium, respectively. Interestingly, similar percentages of captured clusters were obtained when different cuts for the initial radial extent of the cluster populations were considered. For cuts at $0.5R_{\rm t}$ and 10 kpc, we found that 17 ± 3 and 15 ± 3 per cent of SMC clusters were captured by the LMC, respectively. In the latter experiment, we found that 5 ± 3 and 29 ± 7 per cent of the LMC and SMC clusters were ejected into the intergalactic medium, respectively.

We compared the final spatial distribution of the simulated LMC's cluster population with the observed distribution showed by Piatti et al. (2009, see their fig. 10). Since our models can only be compared to the distribution of old halo-like pressure-supported stellar clusters, we selected from the old cluster sample of Piatti et al. (2009) only those with ages $\geq$7 Gyr. Note that this is approximately the time at which the MCs may have started to interact with each other (Besla et al. 2012; Kallivayalil et al. 2013). Using these old clusters we find a mean cluster projected distance with respect to the LMC's centre of approximately 5 kpc. In order to compute the projected distance in our models, we considered the $z = 0$ plane of our simulations as the plane of the sky, and projected the simulated 3D distances on to that plane. Our models with an initial separation between the clouds of 100 kpc and a cut to the cluster's radial distribution at $R_{\rm t}$ yielded a final mean LMC cluster's projected distance of 17 kpc. The large mean distance obtained in these experiments can be attributed to the large cut considered for the initial radial distribution of clusters. In fact, the experiments with an initial separation between the clouds of 60 kpc, and thus a much smaller $R_{\rm t}$ (see Section 2), yielded a projected mean cluster distance of 10 kpc from the LMC's centre. For experiments with cuts at $0.5R_{\rm t}$ and 10 kpc, and initial separation of 100 kpc, we obtained projected mean cluster distances of 16 and 9 kpc, respectively. It is interesting to note that in all cases we found a spatial segregation between the clusters that originally belonged to the LMC and those that were captured from the SMC. For instance, in the simulations with an initial separation of 100 kpc and an initial radial cut at 10 kpc, we found projected mean distances of 7 and 21 kpc for the original and captured LMC clusters, respectively. Although less significant, the same was found in simulations with an initial separation of 60 kpc, where the resulting projected mean distances were 10 and 12 kpc, respectively. Thus, captured SMC clusters are more likely to be found in the outskirts of the LMC.

4 CONCLUSIONS

In this work, we have explored the scenario in which the older and more metal-poor stellar clusters observed in the LMC are, at least partially, a subpopulation of stellar clusters captured from the SMC. For this purpose, we have performed and analysed a suite of numerical simulations of the interaction of MCs in isolation, probing a large number of different orbital configurations and initial radial cluster distributions. The SMC was populated with a distribution of halo-like pressure-supported stellar clusters represented as point masses. In all cases, the simulations were allowed to evolve for three orbital periods, since longer interaction times would likely result in the complete disruption of the SMC (Besla et al. 2012).

It has been long known that tidal interactions between galaxies can result in swapping and loss of stellar clusters from their respective hosts (see e.g. Muzzio 1987). However, this is the first time that this scenario is explored in the context of the interaction between the MCs. Our results show that, for orbits of the SMC about the LMC with eccentricities larger than $e = 0.4$, a total of approximately 15 per cent of the SMC stellar clusters are captured by the LMC. In addition, a fraction of 20–50 per cent of its clusters are expelled into the intergalactic medium.

Not surprisingly, only the least bound clusters are lost by the SMC. As shown by Bekki et al. (2004), the tidal interaction between the MCs can induce the formation of new stellar clusters in the inner regions of the galaxies, especially in the SMC as it is the less massive object and thus more susceptible to the tidal field. However, these newly formed clusters are more tightly bound to its host and thus more likely to remain bound during the interaction. Note that the formation of clusters in the LMC should not be triggered until the LMC has interacted violently with the SMC, much later on, when the pericentric passages of the SMC get sufficiently close to the LMC's centre (approximately 10 kpc apart; Bekki et al. 2004). The final LMC cluster distribution shows an spatial segregation between clusters that originally belonged to the LMC and those that were captured. Clusters that originally belonged to the SMC are more likely to be found in the outskirts of the LMC.

Recently, Piatti & Geisler (2013) presented a detailed comparison of the age–metallicity relationships (AMRs) obtained from field stars and stellar clusters for both the LMC and SMC. Their analysis provided evidence for the formation of stars in the LMC between 5 and 12 Gyr, within the well-known cluster age gap, with almost negligible chemical enrichment. The cluster and field AMRs of the LMC show a satisfactory match only for the last 3 Gyr, while for older ages (>11 Gyr) the cluster AMR is a remarkable lower envelope to the field AMR. On the other hand, the field and cluster AMRs observed in the SMC seem to perfectly agree for the last 7 Gyr, time after which the population of clusters becomes negligible. Interestingly, for ages $\gtrsim$12 Gyr the mean metallicity of the SMC's field stars agrees remarkably well with that of the LMC clusters. This reinforces our hypothesis that, at least partially, the older clusters observed in the LMC were originally members of the SMC's cluster population.

Fully self-consistent hydrodynamical simulations of the interaction of the MCs and the addition of tidal field of the Milky Way would be required to further explore this scenario. We defer this analysis to a follow-up paper.

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