The evolution of primordial binary open star clusters: mergers, shredded secondaries and separated twins

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ABSTRACT

The basic properties of the candidate binary star cluster population in the Magellanic Clouds and Milky Way are similar. The fraction of candidate binary systems is \( \sim 10\% \) and the pair separation histogram exhibits a bimodal distribution commonly attributed to the transient nature of these clusters. However, if primordial pairs cannot survive for long as recognizable bound systems, how are they ending up? Here, we use simulations to confirm that merging, extreme tidal distortion and ionization are possible depending on the initial orbital elements and mass ratio of the cluster pair. The nature of the dominant evolutionary path largely depends on the strength of the local galactic tidal field. Merging is observed for initially close primordial binary clusters but also for wider pairs in nearly parabolic orbits. Its characteristic timescale depends on the initial orbital semi-major axis, eccentricity, and cluster pair mass ratio, becoming shorter for closer, more eccentric equal mass pairs. Shredding or extreme tidal distortion of the less massive cluster and subsequent separation is observed in all pairs with appreciably different masses. Wide pairs steadily evolve into the separated twins state characterized by the presence of tidal bridges and cluster separations of 200-500 pc after one Galactic orbit. In the Galaxy, the vast majority of observed binary system candidates appear to be following this evolutionary path which translates into the dominant peak (25-30 pc) in the observed pair separation distribution. The secondary peak at smaller separations (10-15 pc) can be explained as due to close pairs in almost circular orbits and/or undergoing merging. Merged clusters exhibit both peculiar radial density and velocity dispersion profiles shaped by synchronization and gravogyro instabilities. Both simulations and observations show that, for the range of open cluster parameters studied here, long term binary cluster stability in the Milky Way disk is highly unlikely.

Subject headings: Galaxy: disk – Galaxy: evolution – Open clusters and associations: general – Stars: formation – Methods: numerical
1. Introduction

Observations show that the fraction of potential binary open clusters is not negligible. This finding is not surprising as open clusters are born in star complexes (Efremov 1978, 1995, 2010) with several of these objects being formed nearly at the same time and in close proximity (for a recent review on this topic see, e.g., de la Fuente Marcos & de la Fuente Marcos 2008, 2009a). An early attempt to study this topic by Rozhavskii et al. (1976) concluded that the fraction of multiple systems among open clusters was $\sim 20\%$. Almost two decades later and using a larger sample, Subramaniam et al. (1995) found that about 8\% of open clusters may be genuine binaries. Loktin (1997) further strengthened the idea that multiple open clusters are not uncommon by providing a catalogue of 31 probable multiple systems.

The question of the possible existence of a sizeable fraction of candidate binary clusters in the Galactic disk has been revisited again by de la Fuente Marcos & de la Fuente Marcos (2009b). Using complete, volume-limited samples, they have found consistent and statistically robust figures: at the Solar Circle, at least 12\% of all open clusters could be part of potential binary systems. This number agrees well with the ones previously found by various authors for the Magellanic Clouds (see Dieball et al. 2002 for details). The cluster binary fraction is not only numerically similar; both in the Clouds and Milky Way the pair separation histogram shows a conspicuous bimodal distribution. Yet another common characteristic is the practical absence of close, almost coeval pairs among objects older than about 100 Myr. All this body of solid observational evidence strongly indicates that, if primordial binary star clusters do form, they appear not to be able to survive as such for long. Obvious evolutionary paths include merging, tidal disruption and ionization but, under what conditions merging is favored? what is the characteristic merging timescale? what is the (dynamic/kinematic) signature of an open cluster formed by merging? how does tidal disruption proceed? what happens to ionized primordial pairs? is the initial number of stars in the cluster a factor to consider in the final outcome? can we recover the initial dynamical properties of primordial pairs? are long term stable binary clusters possible at all?

In this work we examine the evolution of simulated primordial binary clusters in an attempt to provide convincing answers to the above questions. This Paper is organized as follows: In §2 we present the simulations. We show our results in §3. In §4 we discuss our results and our conclusions are presented in §5.
2. Simulations

The goal of these simulations is to understand how primordial binary clusters evolve, how they merge when they do, and how the resulting merger remnants look like. We use the direct $N$-body code NBODY6.GPU (Aarseth & Nitadori 2009). This $N$-body code is an improved parallelized version of the standard scalar code NBODY6 (Aarseth 2003) for use with multi-core machines and Nvidia CUDA\footnote{http://www.nvidia.com/cuda}-capable devices. This code has been recently applied to study the dynamics of globular clusters (Heggie & Giersz 2009; Trenti et al. 2010) and it is publicly available from the IoA web site\footnote{http://www.ast.cam.ac.uk/~sverre/web/pages/nbody.htm}.

The initial conditions for each simulation (see details in Table 1) were generated by randomly selecting stellar positions and velocities according to the Plummer distribution (Plummer 1911). The Plummer density profile is given by

\[ \rho(r) = \frac{3M}{4\pi R_p^3} \frac{1}{(1 + (r/R_p)^2)^{5/2}}, \]  

where $r$ is the radial coordinate, $M$ is the total mass of the cluster and $R_p$ is the Plummer radius, a scale parameter which sets the characteristic size of the central regions of the cluster. It is related to the half-mass radius by $R_h \simeq 1.305 R_p$ (Aarseth & Fall 1980; Heggie & Hut 2003). For details on how to set up a numerical Plummer model see Kroupa (2008), also Aarseth et al. (1974). In the simulations, the actual input parameter that defines the initial physical size of the cluster is the virial radius, given by

\[ R_{\text{vir}} = -\frac{GM^2}{4E}, \]  

where $G$ is the gravitational constant and $E$ is the total energy of the system. For a Plummer model the potential energy is (e.g., Binney & Tremaine 2008)

\[ W = -\frac{3\pi GM^2}{32 R_p}, \]  

and $E = W/2$. Therefore,

\[ R_{\text{vir}} = \frac{16}{3\pi} R_p. \]  

Each simulation follows the evolution of two Plummer models in an initially bound orbit. Input parameters are the initial separation (apocloudron distance, $S_o = 10, 20, \text{and } 30 \text{ pc}$)
and orbital eccentricity ($e_o = 0.0, 0.2, 0.4, 0.6, 0.8,$ and 0.95). The apoclustron is function of both semi-major axis and eccentricity, $S_o = a_o(1 + e_o)$. Therefore and if we assume that the two clusters are point-like masses moving in Keplerian orbits, the initial orbital period of the system can be approximated by

$$P_{orb}(\text{Myr}) = 94 \left( \frac{S_o}{1 + e_o} \right)^{3/2} \frac{1}{\sqrt{M_1 + M_2}},$$

(5)

where $M_1$ and $M_2$ are the cluster masses, the apoclustron is in pc and the masses in $M_\odot$ (see actual values in Table 1). Stellar masses in the range $[0.17, 10.0]$ $M_\odot$ are drawn from a Salpeterian IMF with an average stellar mass of 0.5 $M_\odot$. Salpeter (1955) used the observed luminosity function for the Solar Neighborhood and theoretical evolution times to derive an initial mass function (IMF) which may be approximated by a power-law:

$$n(m) \propto m^{-\alpha},$$

(6)

where $n(m)$ is the number of stars per unit mass interval. The value of $\alpha$ is 2.35 for masses between 0.4 and 10.0 $M_\odot$. The IMF used (a single power-law) and the mass range of stars ([0.17, 10.0] $M_\odot$) are equivalent to the realistic canonical two-part power-law over the mass range [0.08, 10.0] $M_\odot$ as described in (e.g.) Kroupa (2008). Neglecting stars more massive than 10 $M_\odot$ is a good approximation since such stars are rare (see, e.g., the $m_{max}$-star cluster mass relation of Weidner et al. 2010). All stars are started on a zero-age main sequence with a uniform composition of hydrogen, $X = 0.7$, helium, $Y = 0.28$, and metallicity, $Z = 0.02$. Stellar evolution is computed according to the algorithm described by Aarseth (2003). Primordial binaries were not included but binary and multiple system formation was allowed and observed. External perturbations were represented by a fixed galactic tidal field. The tidal radius is given by the expression (e.g., Aarseth 2003)

$$R_T = \left( \frac{GM}{4A(A - B)} \right)^{1/3},$$

(7)

where $A$ and $B$ are the Oort’s constants of Galactic rotation. For a star located at that distance from the cluster, the central attraction of the cluster is balanced by the Galactic tidal force. The Oort’s constants are chosen to be $A = 14.4$, $B = -12.0$ km s$^{-1}$ kpc$^{-1}$ (Binney & Tremaine 2008). The cluster pair is assumed to move in a circular orbit at the Solar Circle with no passing molecular clouds (see Aarseth 2003, pp. 127-129, for additional details). No escaping stars were removed from the calculations.

The simulations presented here have been performed on a Dell Precision T5500 + Nvidia Tesla S1070 system. The T5500 has 2 quad-core Intel Xeon E5540 processors at 2.53 GHz,
the S1070 includes 4 GPU cores each with 240 stream processors running at 1.44 GHz for a total of 960 processing units. The Tesla parallel computing architecture is relatively new (Lindholm et al. 2008) but it is already in use for astrophysical applications (e.g. Thompson et al. 2010; Jonsson & Primack 2010; Schive et al. 2010; Trenti et al. 2010).

3. Results

Here we describe the main results for the four different sets of models: 18 models with two equal clusters ($N_1 = N_2 = 4096$, $M = N < m_*$, $q = M_2/M_1 = N_2/N_1$, $q = 1$), 36 models with $N_1 = 4096$, $N_2 = 2048$, $q = 0.5$, 18 models with $N_1 = 4096$, $N_2 = 1024$, $q = 0.25$, and 4 additional control models for single clusters submitted to the same tidal field but with $N = 8192, 6144, 5120$, and 4096, respectively. Calculations were stopped after a simulated time of 210 Myr or one Galactic rotation at the Solar Circle; therefore, all the most interesting phases of the binary cluster evolution could be studied. The state of the system at the end of the simulation is summarized in Table I. The merging timescale has been computed by assuming that a merger takes place if the pair separation becomes less than the average value of the core radius for observed open clusters. The average value of core, half-mass, and tidal radii for real open clusters are 1/2/10 pc (Binney & Tremaine 2008), respectively. This rather conservative merging criterion may appear arbitrary but it responds to what is observed in our calculations: if the pair separation goes under 1 pc, the two clusters quickly merge (see Figure 3). From a strictly observational point of view, star clusters separated by less than twice the core radius are unlikely to be identified as separated objects; therefore, 2 pc could also be a valid (and less conservative) observational criterion for merging.

3.1. $N_1 = N_2$

Figure 1 shows the evolution of the orbital separation for models with two equal orbiting clusters and different initial apocluster and eccentricity. The initial virial radius for the two Plummer models is 1 pc with a mean density of 489 $M_\odot$ pc$^{-3}$. Our numerical results show that two outcomes are possible: merging or a special type of soft ionization. Long term binary stability is not observed. Merging is found in all initially close pairs. Less eccentric pairs take longer to merge, with the circular case taking almost four full initial orbital periods to complete the merging process. For wider pairs, a consistent behavior is also found; clusters

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3http://www.nvidia.com/tesla
gradually increase their separation with the rate of increase slowing down over time. This rate depends on the initial value of the eccentricity of the pair and it is slower for higher eccentricity. An example of merging appears in Figures 2, 3 (model with two clusters in an initially circular orbit and apoclustron 10 pc) and the outcome of ionization after 210 Myr is displayed in Figure 5 (this figure is for a non-equal mass case but the outcome is similar for the equal N case). The ionized clusters that we call “separated twins”, after Theis (2001), are not completely unrelated as a rather conspicuous tidal bridge is always observed. Formation of separated twins is driven by mass loss induced by stellar evolution, two-body relaxation, and (less important) mutual tidal disruption. In relative terms, separated twins retain a proportionally higher fraction of stars, which is not surprising: following Innanen et al. (1972), for two clusters separated by a distance larger than three times the outer radius of each cluster, the amount of mutual disruption is rather negligible. Mergers are less rich in relative terms, as they have lost a fraction of their original stars due to mutual disruption and instabilities during the merging process. The longer the merging process takes, the larger the amount of mutual disruption. In the $X-Z$ plane, merger remnants appear significantly more elliptical than their isolated counterparts (see Figure 2). The merger process imparts rotation to the resulting stellar system in the same sense as the orbital motion (Alladin et al. 1985) due to a tidal torque.

3.2. $N_1 \neq N_2$

Young candidate binary open clusters appear to show a clear trend; in general, the two members of the pair have rather different radii (de la Fuente Marcos & de la Fuente Marcos 2009c). This could be a property intrinsic to open cluster formation in complexes, the result of dynamical interaction, or caused by an observational selection effect. If intrinsic to open cluster formation, primordial binary clusters may ordinarily sport a massive primary and a less massive secondary. On the other hand, not having the same initial population is likely to have an impact on the tidal evolution of the pair. This group of simulations is aimed at studying this case. The primary cluster is as described in the previous section.

3.2.1. $q = 0.5$

Here we explore the evolution of primordial cluster pairs in which the secondary of the system has half the population of the primary, $N_2 = N_1/2$. Two different sub-cases are investigated: i) both clusters have the same stellar density and ii) the secondary is half the size of the primary, i.e. the secondary is denser than the primary.
i) same density

The secondary cluster has a virial radius of 0.79 pc so the mean density is the same for both primary and secondary clusters. The behavior of the orbital separation is similar to that found in the previous section but the soft ionization process is slightly slower (see Figure 4). The merging timescale is also affected: mergers for models with $e_o > 0.5$ take longer now but those for less eccentric pairs are faster. Merging is only observed for models with an initial apoclonstron distance of 10.0 pc. Cores of merger remnants are more extended than those observed in the previous case.

ii) different density

The secondary cluster has a virial radius of 0.5 pc with a mean density of $1956 M_\odot pc^{-3}$. The behavior of the orbital separation is similar to that found in the previous section (see Figure 6). This is to be expected: a study by Sensui et al. (2000) showed that the internal structure of galaxies does not play a role in the merging time-scales (inside a galaxy cluster) – only the distribution of galaxies inside the cluster matters. This argument should also hold for star clusters in a star cluster complex (Fellhauer et al. 2002, 2009). The single main difference appears for highly eccentric models in which merging is observed in two cases (as in $N_1 = N_2$): $S_o = 10.0$ and 20.0 pc.

3.2.2. $q = 0.25$

This set of simulations is designed to study the impact of enhanced tidal forces on the secondary cluster. With a virial radius of 0.63 pc, it still has the same reference mean density used throughout this study. The dynamical behavior of the pair is now substantially different (see Figure 7). The tidal disruption timescale is much shorter than that for merging. Eventual destruction of the less massive cluster is observed in all cases, including close pairs. In some cases, the secondary cluster appears extremely distorted and elongated with no clearly identifiable core (see Figure 8): in other words, the secondary cluster gets torn apart in a relatively short timescale. Technically speaking, shredded clusters are different from typical open cluster remnants, they look more like stellar streams and they may be rather young. Remnants of shredded clusters may show up in kinematic studies even if they cannot be detected as stellar overdensities. Tidal shredding is a form of shearing by differential rotation. The secondary cluster in proximity to the most massive primary becomes stretched out by tidal forces. The secondary distends and flattens in the direction of the primary evolving as to minimize its gravitational potential energy becoming an ovoid
stretched along the axis connecting the two bodies. Figure 9 shows the early evolution of the model displayed in Figure 8. The secondary cluster undergoes early rapid expansion mainly due to stellar mass loss. In addition, the characteristic timescale for equipartition of kinetic energy is much shorter for the secondary cluster contributing to its overall faster internal dynamical evolution. Coupling of these two processes effectively drives the cluster away from equilibrium as the total potential energy per unit mass quickly decreases. This behavior is, in principle, similar to the one described in Portegies Zwart & Rusli (2007): the secondary expands quickly initiating mass transfer to the primary. There is, however, a major difference: extreme tidal distortion is not observed in their models (see comments below). In our calculations and as the massive companion’s gravitational pull is stronger on the overextended secondary cluster’s near side than on the far side, the secondary cluster is literally shredded with the help of the galactic tidal field.

3.3. Control models

For the purpose of comparison, we computed four single Plummer models with consistent tidal field: the virial radii were 1.26, 1.14, 1.08 and 1.00 for a mean density of 489 $M_\odot$ pc$^{-3}$. The rest of the details of the simulation are common to the binary simulations. After 210 Myr the values of the core, half-mass, and tidal radii were 0.095/1.92/18.0 pc ($N = 8192$), 0.106/2.23/18.0 pc ($N = 6144$), 0.37/2.62/18.0 pc ($N = 5120$) and 0.34/2.61/18.0 pc ($N = 4096$). The average values of the same magnitudes for the merged clusters were: 0.29/4.17/22.6 pc ($q = 1.0$) and 4.35/6.37/20.5 pc ($q = 0.5$). The central regions of merger remnants are significantly more extended than those of equivalent single models. Merger remnants are less populated than an equivalent single cluster of the same age as a result of mutual disruption of the pair during the merging process.

3.4. How realistic are these models?

Typical densities of candidate bound open clusters younger than 13 Myr are in the range 4-400 $M_\odot$ pc$^{-3}$ (Wolff et al. 2007) with the upper limit represented by $\chi$ and $h$ Persei. Slesnick et al. (2002) estimated that the total mass of the stars with $M > 0.1 M_\odot$ in $h$ and $\chi$ Persei is 3700 and 2800 $M_\odot$, respectively, although these are, probably, lower limits for the masses of these clusters. Therefore, the characteristics of the simulated clusters match well those of the most massive classical open clusters. These are the ones expected to be able to survive for several Galactic rotations and, therefore, statistically speaking more likely to be observed. Their values are, however, far from those typical of starburst clusters with
densities in the range $10^3$ to several $10^5 \, \text{M}_\odot \, \text{pc}^{-3}$ and $N = \text{several} \, 10^4 - 10^5$ (see, e.g., Pfalzner 2009). Similar trends have been found for star clusters in other galaxies (Pfalzner & Eckart 2009).

4. Discussion

The above results can only be properly understood within the context of the Galactic tidal field; i.e. cluster tidal radii and separations play a major role in the outcome of primordial binary cluster evolution. The strength of the cluster-cluster interaction is maximum when the intercluster separation becomes smaller than the tidal radii. This interpretation was proposed in de la Fuente Marcos & de la Fuente Marcos (2009c) in the form of a classification scheme (8) based only in the values of separation ($S$) and tidal radii ($R_{T_i}$, $i = 1, 2$):

\[
\text{Cluster Pairs} \begin{cases}
\text{Detached}, & R_{T1} + R_{T2} < S \\
\text{Interacting}, & R_{T1} + R_{T2} > S
\end{cases}
\begin{cases}
\text{Weak}, & R_{T1} \text{ AND } R_{T2} < S \\
\text{Semi-Detached}, & R_{T1} \text{ OR } R_{T2} < S \\
\text{In-Contact}, & R_{T1} \text{ AND } R_{T2} > S
\end{cases}
\]

The scheme was implemented by considering the available observational evidence. For open cluster pairs of similar mass ratio in the detached and weakly interacting categories, ionization into the separated twins state is the observed evolutionary path. Semi-detached and in-contact pairs merge in a timescale that depends strongly on the orbital eccentricity. Very eccentric pairs merge in a timescale of nearly 10 Myr and, therefore, the actual observation of the merging process may be very difficult as it may happen even before the embedded phase ends. If the mass ratio is appreciably different, extreme tidal distortion followed by actual destruction of the smallest cluster is always observed. The above interpretation has strong implications on what should be observed within the Milky Way at different Galactocentric distances and in other galaxies. Weaker galactic tidal fields increase the probability of observing semi-detached or in-contact cluster pairs and, eventually, mergers. The tidal force gradient determines the cluster tidal radius (e.g. Elmegreen & Hunter 2010). Even if the fraction of primordial binary clusters may well be similar across different galaxies, the preferential evolutionary path could be rather different: ionization being dominant in massive galaxies and the central regions of galaxies in general.
4.1. How do these results compare with actual data?

Figures 1, 4, 6 and 7 also show probable primordial pairs (age difference <30 Myr) with pair age < 210 Myr. Following de la Fuente Marcos & de la Fuente Marcos (2009b), the pair age is assumed to be that of the youngest cluster in the pair. The agreement is very significant. Most pairs, if primordial, appear to be evolving towards the separated twins state. As expected, the observed number of close pairs is consistent with short merging timescale. Only seven pairs in the figures (see also Figure 10) appear to be in a bound state: NGC 1976/NGC 1981, ASCC 20/ASCC 16, Collinder 197/ASCC 50, NGC 6250/Lynga 14, NGC 3324/NGC 3293, NGC 6613/NGC 6618, and Trumpler 22/NGC 5617. Another candidate (not in the figure) to bound pair is Loden 1171/Loden 1194 (see de la Fuente Marcos & de la Fuente Marcos 2009b for details). Both Trumpler 22/NGC 5617 and Loden 1171/Loden 1194 seem to be the evolved state of primordial pairs with almost circular initial orbits and original separation < 20 pc. The possible triple cluster NGC 1981/NGC 1976/Collinder 70 is a singular object with the inner pair probably undergoing merging. Some of these binary candidates are displayed in Figure 11. Out of the clusters in this figure, the pairs NGC 3324/NGC 3293 and Trumpler 22/NGC 5617 may be actual bound clusters. In contrast, the pair NGC 659/NGC 663 is likely evolving into the separated twins state. Another example of bound clusters could be the cluster pair NGC 3590/Hogg 12. Piatti et al. (2010) have pointed out this pair as a strong open cluster binary system candidate. Both clusters have similar ages (30 Myr), reddenings and metallicities. They appear to be located at 2 kpc from the Sun and at that distance the pair separation is a mere 3.6 pc. In this case (see Figure 12), one of the clusters (Hogg 12) seems to be undergoing extreme tidal distortion. A dramatic example of ongoing merger candidate is the case of the partially embedded massive young cluster NGC 2244 described by Li (2005) where two structures may be separated by just ∼ 7 pc. Regarding the remarkable double-peaked pair separation distribution observed for young open cluster pairs (de la Fuente Marcos & de la Fuente Marcos 2009b), the vast majority of observed candidates evolve into separated twins which translates into the dominant peak (25-30 pc) in the pair separation distribution. The secondary peak at smaller separations (10-15 pc) can be explained as due to close pairs in almost circular orbits or undergoing merging. The average tidal radius of open clusters at the Solar Circle is nearly 20 pc. Therefore, cluster pairs with original separations smaller than the cluster tidal radius are likely to merge but those born with wider separations are bound to evolve into the separated twins state. Our calculations show that only equal-mass pairs formed with originally small separations and nearly circular orbits are likely to be observed in close proximity for more than 100 Myr and actually pose as genuine binary open clusters. In summary, the bimodal distribution observed in the pair separation histogram is the result of evolutionary effects and not of different formation channels.
4.2. How can we identify merger remnants?

Separated twins are, in principle, easy to identify; just think about the Double Cluster in Perseus (see caption in Figure [5]). But, what about merger remnants? One easy to implement test is based on star counts. Figure 13 shows the surface number density profile for models with \( q = 1 \) at 210 Myr. Two single models with \( N = 8192 \) and 4096 evolved in a similar tidal field and a King profile (King 1962) are also included as reference. The outer regions of merger remnants are similar to those of an equivalent single cluster having twice the population of the individual clusters but the number density of the inner regions is rather different. In general, merger remnants are expected to be fainter. However, some models ending in merger show clear central cusps which are absent from single models. Merger models characterized by higher central concentration are preferentially associated to pairs with high initial eccentricity and, therefore, shorter merger timescale. They are also the pairs in which the mutual tidal disruption has been the weakest as they have been interacting for a shorter period of time. This explains why their cores are nearly 25-50% denser than that of an equivalent King model. In contrast, mergers of low eccentricity pairs have lower central densities. This is the result of longer merger timescale and enhanced mutual tidal disruption. This lower density translates into higher production of hierarchical systems in the form of temporarily stable triple and quadruple stellar systems with respect to single models. This is to be expected as higher stellar density increases the probability of relatively close-range gravitational interactions that quickly destroy multiple systems. In general, the central regions of merger remnants are distinctively different from those of clusters evolving without companions but haloes look very similar.

Regarding the kinematic signature of merging, it is also obvious in the central regions. Data in the figures discussed here are referred to the center of masses of the merged/single cluster. In this analysis we use the root mean square velocity defined as the square root of the average velocity-squared of the stars in the cluster, their radial velocity and transverse velocity. The \( V_{rms} \) is always greater than or equal to the average as it includes the standard deviation \( (V_{rms}^2 = < V^2 > + \sigma^2) \). The radial velocity is given by

\[
V_r = \frac{\vec{v} \cdot \vec{r}}{|\vec{r}|},
\]

where \( \vec{r} \) is the position of the star and \( \vec{v} \) its velocity. Finally, the transverse velocity is defined by

\[
V_t = \frac{|\vec{r} \times \vec{v}|}{|\vec{r}|}.
\]

The transverse velocity is also the product of the angular speed \( \omega \) and the magnitude of the position vector. Therefore and for a given star cluster region, transverse velocity and angular
speed exhibit the same behavior: both increase or decrease concurrently. The modulus of the specific angular momentum is the magnitude of the position vector times the transverse velocity. Figure 14 shows the rms velocity for concentric shells similar to those in Figure 13 for merged models and the two reference single models already presented. The value has been summed over all the stars in the shell considered and divided by the number of particles inside that shell. In general, the outcome of a typical merged model shows a value of the rms velocity in the core intermediate to those of the reference models and it gets closer to that of the most massive reference model in the outer parts of the cluster. The behavior beyond the half-mass or effective radius is similar for all the models, the rms velocity decreases gradually outwards. It is, however, not so clear how this peculiar velocity distribution can be used to identify merger remnants. The behavior of the radial velocity profile in Figure 15 is, however, easier to interpret. In mergers, radial velocities tend to be lower or even negative in the central regions of the cluster (see Fig. 3, top panel in Baumgardt et al. 2003). This trend is observed in several of the studied cases and it may point out collapse of the central regions induced by the gravogyro instability (see below) or to statistical fluctuations. The transverse velocity profile is displayed in Figure 16. In general and up to 10 pc from the center of the merger these profiles are very smooth. The value of the transverse velocity in the central pc of the merger remains remarkably constant in clear contrast with what is observed for single cluster models. This can be interpreted as evidence for a moderate amount of global rotation. On theoretical grounds (King 1961), rotation causes a slight increase in the rate at which a cluster is losing stars. This is consistent with the relatively smaller final population observed in merged models.

### 4.3. Mergers, synchronization and gravogyro instabilities

Single self-gravitating and globally rotating $N$-body systems are affected by a little known instability that is playing a role here: the gravogyro instability. Initially proposed by Inagaki & Hachisu (1978) and Hachisu (1979, 1982) and further studied by Akiyama & Sugimoto (1989) using numerical techniques, the gravogyro instability or gravogyro catastrophe is triggered when specific angular momentum is removed (by escaping stars) from the cluster and a deficit in the supporting centrifugal force is induced. In other words, the escape of stars from the core to the outer regions transports angular momentum from the inner regions of the cluster to the outer parts. As a result, the inner regions react to compensate the loss of centrifugal force contracting in order to increase rotation. Faster rotation induces additional mass loss. The gravogyro effect increases the average angular speed of the central regions of the cluster decreasing the average value of the local angular momentum. The overall result is faster dynamical evolution of the star cluster and higher mass loss. The
gravogyro instability leads to further mass loss through the galactic tidal boundary. This process causes the contraction of the core of the star cluster as observed in Figure 13 (models with $e_o = 0.2$ and 0.6, mainly).

But before the onset of the gravogyro instability, a merger must take place in order to have a rotating system. This is the result of yet another instability: the synchronization instability. The numerical/theoretical work of Sugimoto & Makino (1989) and Sugimoto et al. (1991) showed that binary star clusters undergo an instability at a critical separation and this process is able to trigger rapid merging of star clusters. The orbit of the bound cluster pair circularizes and shrinks due to the loss of angular momentum carried away by escaping particles. As the separation of the binary system decreases, the orbital period of the binary becomes shorter and the mutual tidal effects stronger. Concurrently, the spin of each cluster increases following the orbital motion due to the induced tidal torque attempting to synchronize cluster rotation and orbital period. This transformation of orbital angular momentum into rotational angular momentum leads to an instability at a critical separation when the exchanged orbital angular momentum becomes insufficient to supply the necessary angular momentum for spin synchronization. At that moment merging takes place as the orbital angular momentum is no longer capable of balancing the gravitational attraction between the two star clusters. Figures 1, 4 and 6 clearly indicate that in our models and after the pair separation becomes $< 2$ pc, merging proceeds very quickly. The gyration radius of a self-gravitating system of stars can to first-order be approximated by $R_{\text{vir}}$ (e.g., Portegies Zwart & Rusli 2007); therefore, merger occurs when the intercluster separation falls below twice the gyration radius. This process is similar to the tidal locking effect observed in planetary systems. The main difference here is that in planet-satellite interactions both conversion of orbital angular momentum into spin and vice versa are possible. On the other hand and in absence of dissipation (drag forces), the outcome of tidal locking is always a stable binary configuration not a merger as in the case of star clusters. The main reason for the lack of stable outcome in the case of star clusters is that the total angular momentum is not actually preserved as stellar evolution, rotation-induced escapees (those resulting from the gravogyro effect), and two-body relaxation are concurrently and constantly removing angular momentum from the system. The total angular momentum removal rate depends on many factors, the age of the cluster being one of them. Other facts to consider here are the masses of the clusters, the mass ratio, and the galactic tidal field.

The gravogyro and synchronization instabilities are somehow related as they involve rotation and transfer of angular momentum but they are not the same process. For originally non-rotating, merging clusters, synchronization occurs first and then, eventually and after global cluster rotation is induced, the gravogyro instability starts on the resulting merger. The final phases of the synchronization instability and the onset of the gravogyro instability
overlap; in fact, and as described above, the enhanced escape rate caused by the gravogyro instability helps to deplete the remaining orbital angular momentum. The most dramatic example is observed for the slowest merging model, the one with $e_o = 0.0$.

Single star clusters formed out of unstable disks might exhibit some degree of primordial rotation. Ernst et al. (2007) studied $N$-body models of rotating globular clusters to confirm that the gravogyro instability takes place in monocomponent clusters (clusters with equal-mass stars). They found that the $z$-component of the specific angular momentum decreases over time for the inner regions of the clusters increasing, in return, the average angular speed of the same areas (and therefore the transverse velocity); see their Figs. 3 and 4. For these models the effect is very important with a significant amount of angular momentum being transferred outwards. The induced deficit of centrifugal force triggers the collapse of the core of the star cluster. If the Galactic tidal field is included in the calculations, rotation increases the escape rate dramatically. In sharp contrast, their models of systems with two-mass components (two mass groups for a very simple IMF) show that the effect of rotation is rather negligible. In this case and if rotation is primordial, two concurrent processes are at work: mass segregation and rotation. Both compete to accelerate the collapse of the cluster core but mass segregation clearly dominates. In summary, they found that if energy equipartition is at work the role of rotation is somewhat secondary but in absence of energy equipartition, rotation through the gravogyro effect speeds up and controls the evolution of the cluster. This is what we observe in our models. Figures 17 and 18 show the evolution of the average value of the transverse velocity for relevant concentric cluster shells (see the caption for details) of two representative models: the ones with the longest and shortest, respectively, merging timescale. By the time ($\sim 150$ Myr) the clusters in the slowest merging model actually merge, energy equipartition has been achieved and the gravogyro effect is the strongest. Conversely, the fastest merging model shows that rotation is quickly lost from the merger remnant through energy equipartition; the time evolution of the average transverse velocity being similar to that of a single cluster model with $N = 4096$. As for the time evolution of the $z$-component of the specific angular momentum in our models, representative results are displayed in Figs. 19 and 20. For the slowest merging model and after merging, systematic loss of angular momentum is observed with the outer regions sporting the largest share of angular momentum. In the case of an early merger, angular momentum also decreases over time but the magnitude of this angular momentum is much higher and positive as expected for a rotating system.
4.4. How do these results compare with those from previous works?

Unfortunately, little attention has been devoted to the topic of binary cluster evolution. In a ground breaking paper, Sugimoto & Makino (1989) used $N$-body simulations to study the merging timescale of two identical star clusters ($N = 2048$). They found that the interaction provoked circularization of the orbits of the clusters and synchronization of the spin of each cluster with its orbital revolution. The loss of orbital angular momentum caused the eventual demise of the pair. The entire process was described by them as the synchronization instability. This phenomenon is also responsible for merging in our models. Their work was continued in Makino et al. (1991) for non-equal clusters. Merging of two stellar systems usually gives surface density profiles $\Sigma(r) \propto r^{-3}$ (Sugimoto & Makino 1989; Makino et al. 1990; Okumura et al. 1991). In our models this is only true for the outskirts of merger remnants; the central regions can be better described by $\Sigma(r) \propto r^{-1}$ or $r^{-2/3}$ (see Figure 13). Using analytical arguments, Ballabh & Alladin (2000) showed that merging always occurs if the distance of closest approach is about twice the sum of the dynamical radii of the clusters. This is confirmed by our calculations. De Oliveira et al. (2002) used $N$-body simulations to study the dynamical status of the cluster pair NGC 1912/NGC 1907. Their simulations found the formation of stellar bridges similar to the ones found in our calculations. Faster encounters produce weaker tidal debris in the bridge area. Our simulations are also consistent with this result.

The most realistic simulations of binary cluster evolution so far have been performed by Portegies Zwart & Rusli (2007) using the kira integrator of the starlab simulation environment. Their calculations were aimed at understanding the nature of the cluster pair NGC 2136/NGC 2137, in the Large Magellanic Cloud. Their models are, therefore, more massive; their primary clusters have $N$ in the range $[9,000, 24,855]$ with smaller secondaries moving in circular orbits. They found that cluster pairs with initial separation smaller than 15-20 pc merge in $<60$ Myr. Pairs with larger initial separation tend to become even more widely separated over time. In spite of the different code and initial conditions used, our results are, in general, fully compatible with theirs. There is, however, a major difference induced by the fact that they do not take into account the background galactic tidal field. They did not observe the extreme tidal distortion displayed in Figure 13. Besides, they only follow their models for about 100 Myr. Their main models have $q = 0.167$; this value triggers catastrophic destruction in our models. The soft ionization widely found in our simulations was originally described in a series of little known but very interesting papers (Theis 2001, 2002a,b). Within the context of globular cluster formation, Theis’ simulations found that identical twin clusters may merge or evolve into well separated twins sharing a common galactic orbit.
Our calculations clearly show that the impact of merging on the evolution of close and therefore young open cluster pairs is all but negligible. The same can likely be said about young star cluster pairs in other galaxies. On the other hand, the rapid decrease in star cluster numbers for ages older than 20 Myr (infant mortality) observed in our Galaxy and others and usually attributed exclusively to the catastrophic gas ejection mechanism originally proposed by Hills (1980) can also be the result of merging or tidal disruption in close primordial pairs. Merging and tidal disruption of the less massive companion may easily halve (at least) the initial population of relatively close open cluster pairs. Merging, disruption and infant mortality, concurrently, can efficiently reduce the number of observed young star clusters and accelerate dramatically the transition of stars born in clusters to the field populations.

It may be argued that the loss of clusters through merging can only be significant if the fraction of binary clusters at birth is high, but is the primordial semi-major distance distribution supportive of this? If the Orion Nebula star forming complex could be considered as representative of the kind of environment in which most open clusters actually form, the answer may be in the affirmative. Current available evidence (de la Fuente Marcos & de la Fuente Marcos 2009b) suggests that the group NGC 1981/NGC 1976/ Collinder 70/σ Ori may form several close pairs, all of them with separations < 30 pc and few Myr old. There is also a statistical tool that may help to understand the timeline of the relative importance of these processes: the generalized fractal dimension or multifractal analysis. De la Fuente Marcos & de la Fuente Marcos (2006) showed that the generalized fractal dimension changes very significantly for clusters younger than 40 Myr but remains almost constant for older clusters. Catastrophic gas ejection is an essentially self-driven process and operates on all scales; merging or extreme tidal distortion only operates on small length-scales within star-forming complexes where the typical intercluster distance is < 30 pc. Processes operating on all scales keep the value of the generalized fractal dimension almost constant across the multifractal spectrum. The opposite is observed when processes operate only for objects in close proximity. Our numerical results are consistent with the fractal dimension results if most pairs are born in originally very eccentric orbits (e > 0.5) and/or with very different masses. Those are the ones merging (or being tidally destroyed) within 40 Myr of forming.

5. Conclusions

Using available observational evidence, de la Fuente Marcos & de la Fuente Marcos (2009b) have demonstrated that the population of binary open clusters is statistically significant and that the fraction of candidate binary clusters in the Milky Way disk is comparable
to that in the Magellanic Clouds, \( \sim 10\% \). Out of this population, nearly 40\% of them can be classified as genuine primordial binary open clusters although only a relatively small fraction (\( \sim 17\% \)) appear to be able to survive as conspicuous pairs for more than 25 Myr. The distribution of open cluster separations exhibits an apparent peak at 10-15 pc, analogous to the one observed in both LMC and SMC. Here, we have used \( N \)-body simulations in an attempt to understand how primordial binary open clusters evolve and what initial orbital elements are required in order to explain their observed properties. Vázquez et al. (2010) concluded that available observational evidence indicates that double cluster lifetimes are short and that is what simulations confirm. Our main conclusions can be summarized as follows.

1. Long term stability of binary open clusters appears not to be possible. Primordial binary open clusters seem to be inherently transient objects, at least for the range of cluster parameters explored here.

2. The results of our simulations interpreted within the context of the available observational data clearly indicate that the vast majority of primordial binary open clusters gradually evolve into well separated objects. After one Galactic rotation the separation is in the range 200-500 pc but they exhibit relatively prominent tidal bridges. Formation of separated twins is driven by mass loss induced by stellar evolution, two-body relaxation, and mutual tidal disruption.

3. Close primordial binary open clusters quickly merge into a single object. The merging timescale depends on the orbital and physical characteristics of the pair. Most close pairs merge within 100 Myr of formation. For eccentric pairs the merging scale is even shorter, about 50 Myr. Our numerical results and the short characteristic observational survival time for candidate primordial pairs, 25 Myr, strongly suggest that nearly 80\% of primordial binary open clusters are born in systems with orbital eccentricities \( > 0.5 \). Merging is driven by the synchronization instability.

4. For clusters pairs of appreciably different masses extreme tidal distortion or shredding of the secondary is observed, causing the complete disruption of the less massive cluster within one Galactic orbit. Remnants of shredded clusters may show up in kinematic studies even if they cannot be detected as stellar overdensities.

5. The gravogyro instability shapes the spatial and kinematic structure of merger remnants but the effect is only dominant for primordial pairs in almost circular orbits.

6. The observed candidate pair separation histogram shows a bimodal distribution. In the light of the present results, the two peaks are mainly the result of ionization and
merging. They do not appear to be the result of different formation channels but different evolutionary paths.

7. The sharp decline in open cluster numbers observed for objects older than about 20 Myr can be explained by three different processes operating concurrently: catastrophic gas expulsion, tidal disruption and merging. This can efficiently reduce the number of observed young star clusters and accelerate dramatically the transition of stars born in clusters to the field populations.

It has often been assumed that binary open cluster formation in the Milky Way is uncommon. In contrast, our results indicate that the lives of primordial binary clusters are violent and hazardous. Close pairs (if formed) merge in a short timescale, being the shortest for very eccentric pairs, secondaries in low mass ratio pairs are rapidly destroyed, and wide pairs quickly ionize in the background tidal field due to mass loss. As open clusters are actually born in close proximity (complexes), these appear to be the genuine reasons behind the apparent lack of binary open clusters in our Galaxy. Star cluster binarity is, therefore, a transient phenomenon.

The effects and trends observed in the present set of simulations are robust for the range of open cluster parameters studied. As usual, it is potentially dangerous to make unwarranted extrapolations to larger/smaller or denser clusters. It could be possible that for much larger and denser star clusters the merging timescale is longer. Nevertheless, the absence of binary globular clusters in the Milky Way appears to indicate that long-term binary cluster stability is, in fact, unlikely. The role of the gravogyro effect of the evolution of merger remnants appears to be well documented in our present work but larger simulations are needed to better understand the statistical strength of this process.

The authors would like to thank S. Aarseth and K. Nitadori for providing the code used in this research. The authors also would like to acknowledge the help of J. L. Mazo Frías, N. Pedone, and P. Chan of Dell Computer with the T5500+S1070 system. In preparation of this paper, we made use of the NASA Astrophysics Data System and the astro-ph e-print server. This research has made use of the WEBDA database operated at the Institute of Astronomy of the University of Vienna, Austria. This work also made use of the ALADIN, SIMBAD and VIZIER databases, operated at the CDS, Strasbourg, France.
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Fig. 1.— Evolution of the orbital separation for models of two clusters with $N = 4096$ for a total of 8192 stars. The three curves on each panel are for initial separations (apoclustron distance) 10, 20, 30 pc and the value of the initial orbital eccentricity indicated on the panel label. For merged models, cluster centers were computed only using stars within 30 pc of the pair centers. The points correspond to actual open cluster pairs from the de la Fuente Marcos & de la Fuente Marcos (2009b) study. The sample displayed is made of pairs with age difference $< 30$ Myr, separation $< 500$ pc and age $< 210$ Myr. The age of the pair is that of its younger member.
Fig. 2.— Merging: representative snapshots in the $X - Y$ plane (top) and the $X - Z$ plane (bottom) of the evolution of the model with $q = 1.0$, $S_o = 10.0$ pc (initial separation, apoclustron distance), and $e_o = 0.0$. Color is related to the mass of the simulated star in $M_\odot$ according to the key provided. Merging for this model is the slowest of all the models ending in merging. Once the two clusters get closer than 2 pc merging proceeds very quickly. The $X$ axis points towards the galaxy center, $Y$ is tangent to the galactocentric pair motion, and $Z$ is perpendicular to the galaxy plane. For real open clusters, we do not have access to the $X - Y$ view. In the $X - Z$ plane, the merger remnant looks significantly more elliptical than the single/individual cluster. By the end of the simulation all the stars more massive than about 3.8 $M_\odot$ have already evolved away from the main sequence. More massive objects are all stellar remnants or (less frequently) stellar mergers. No objects were removed from the calculations. The initial orbital period was nearly 46 Myr.
Fig. 3.— The trajectory of the center of masses of the merging clusters for the model displayed in Figure 2. The time difference between consecutive points is 2.33 Myr.
Fig. 4.— Same as Figure II but for models with $q = 0.5$ and the same average density.
Fig. 5.— Separated twins: representation in the $X - Y$ plane (top) and the $X - Z$ plane (bottom) after 210 Myr for the model $q = 0.5$ (equal average density), $S_o = 20.0$ pc and $e_o = 0.95$. Gradual separation is the slowest for this model. For other models following this evolutionary path the main difference is in the larger separation at 210 Myr. The famous Double Cluster ($h + \chi$ Persei pair, NGC 869/NGC 884) is a clear prototype for this pair type (actual physical separation $> 200$ pc). Another obvious candidate is the pair NGC 659/NGC 663 (see de la Fuente Marcos & de la Fuente Marcos 2009b for details). Colors are as in Figure 2.
Fig. 6.— Same as Figure 4 but for models with $q = 0.5$ and different average density (see the text for details). Density appears to have a minor role on the overall evolution of the cluster pair.
Fig. 7.— Same as Figure 1 but for models with q = 0.25 and the same average density. This result is different from that found by Portegies Zwart & Rusli (2007) but their simulations do not take into account the background galactic tidal field.
Fig. 8.— Shredding of the secondary: representative snapshots in the $X-Y$ plane (top) and the $X-Z$ plane (bottom) of the evolution of the model with $q = 0.25$, $S_o = 10.0$ pc, and $e_o = 0.95$. Colors are like in Figure 2. Extreme tidal distortion of the less massive cluster and subsequent separation is observed for all pairs with appreciably different mass ratio. The identifiable cluster at 133, 210 Myr is the primary. The secondary cluster gets shredded in a relatively short timescale (see Fig. 9). The $X$ axis points towards the galaxy center, $Y$ is tangent to the galactocentric pair motion, and $Z$ is perpendicular to the galaxy plane. For real open clusters, we do not have access to the $X-Y$ view.
Fig. 9.— Early evolution of the model displayed in Figure 8. This behavior is similar to the one identified by Portegies Zwart & Rusli (2007): the initially less massive cluster expands quickly initiating mass transfer to the more massive cluster. Fast expansion of the secondary cluster is the result of stellar mass loss (see the text for details). As for observed open clusters, de la Fuente Marcos & de la Fuente Marcos (2009c) concluded that binary cluster candidates in the Galactic disk appear to show a tendency to have components of different physical size. Our results clearly indicate that this effect may well be the result of dynamical interactions.
Fig. 10.— Comparison between the time evolution of the pair separation in models of two clusters with $N = 4096$ (detail of Figure I) and real data for strong candidates to be undergoing merging from de la Fuente Marcos & de la Fuente Marcos (2009b) study. The sample displayed (symbol, age, separation, heliocentric distance) includes NGC 1976/NGC 1981 (+, 13 Myr, 7 pc, 400 pc), ASCC 20/ASCC 16 (×, 8 Myr, 13 pc, 460 pc), Collinder 197/ASCC 50 (*, 13 Myr, 20 pc, 838 pc), NGC 6250/Lynga 14 (□, 5 Myr, 21 pc, 865 pc), NGC 3324/NGC 3293 (filled □, 6 Myr, 21 pc, 2327 pc), and NGC 6613/NGC 6618 (⊙, 1 Myr, 22 pc, 1296 pc). The cluster pair Trumpler 22/NGC 5617 (not shown in this plot) may also be in this category (82 Myr, 21 pc, 1516 pc). The age difference of all these pairs is <
Fig. 11.— Examples of real candidate binary clusters cited in the text. In principle, only the NGC 659/NGC 663 pair (age 16 Myr, separation 25 pc, distance 1938 pc) appears to be following the ionization evolutionary path. Images credit (North is up, East to the left): (NGC 659/NGC 663) POSSLE-DSS1 frame, 2.0×1.4 deg², epoch 1954.75111225188; (NGC 3293/NGC 3324) POSSI.V-DSS1 frame, 1.0×0.7 deg², epoch 1987.05060651; (NGC 5617/Trumpler 22) SERC.J-DSS1 frame, 1.0×0.7 deg², epoch 1976.1923587345. The NGC 5617/Trumpler 22 image also includes the smaller and relatively old (1 Gyr) open cluster Pismis 19 (or vdBH 160) north from Trumpler 22 and southeast from NGC 5617. This cluster may be interacting with the other two (de la Fuente Marcos & de la Fuente Marcos 2009b).
Fig. 12.— The NGC 3590/Hogg 12 cluster pair is another strong candidate to undergo merging. Piatti et al. (2010) have concluded that Hogg 12 is a strongly depleted but real open cluster and that both open clusters are located 2 kpc from the Sun. The pair separation is just 3.6 pc and both clusters have similar age (30 Myr), reddening and metallicity (solar). These authors suggest that it is a strong open cluster binary system candidate. Image credit: ESO.R-MAMA, 0.66 μm, frame, 11.52×11.52 arcmin², epoch 1980.07527720739 (North is up, East to the left).
Fig. 13.— Radial density profile (top) for merger remnants with $q = 1.0$ at 210 Myr. Two single models with $N = 8192$ (I), 4096 (II) evolved in a similar tidal field and a King profile are included for comparison. The outer regions of merger remnants are similar to those of an equivalent single cluster but the number density of the inner regions is a factor 2 lower (150 vs. 300 stars pc$^{-2}$) than that of reference model (I) and close to that of model (II). However, some models show clear cusps which are absent from single models. The core of merger remnants from originally eccentric pairs ($e > 0.6$) is always denser than that of an equivalent King profile with similar behavior in the outskirts. Mergers from eccentric pairs take place more rapidly; therefore, the timescale for merging strongly affects the final, observed density profile. The most unusual profiles are associated to the models with the longest merging timescales ($e = 0.0, 0.2, 0.6$). These profiles are $\Sigma(r) \propto r^{-2/3}$ in the central regions. Merging of two stellar systems is expected to give surface density profiles $\Sigma(r) \propto r^{-3}$ (Sugimoto & Makino 1989; Makino et al. 1990; Okumura et al. 1991). This also translates into very peculiar velocity profiles (see Figs. 14, 15 and 16).
Fig. 14.— Root mean square velocity profile for the same merged and single clusters in Fig. 13 after 210 Myr. The rms value is always greater than or equal to the average as it includes the standard deviation as well. In general, the rms velocity of the central regions of merger remnants is significantly lower than that of an equivalent single cluster with $N$ equal to twice the population of the merged clusters but just slightly higher than that of a cluster with the same population of the individual clusters. The outer regions are more similar to those of the larger $N$ cluster. Velocities are referred to the cluster or merger center of masses (CM).
Fig. 15.— Radial velocity profile for the same merged and single clusters in Figs. 13 and 14 after 210 Myr. In general, the average radial velocity of the central regions of merged clusters is lower than that of the single model with $N = 4096$. The standard deviation is however nearly 40% the average value; therefore, the profiles are consistent. Velocities are referred to the cluster or merger CM.
Fig. 16.— Transverse velocity profile for the same merged and single clusters in Figs. 13, 14 and 15 after 210 Myr. In general, transverse velocity profiles for mergers are very smooth. In the halo of the cluster they match that of an equivalent single cluster with $N$ equal to twice the population of the pre-merger cluster. However, in the inner regions the average transverse velocity is significantly lower, similar to that of a cluster with the same population of the individual pre-merger clusters. Beyond 10 pc from the center profiles are very similar. The model with the longest merging timescale ($e = 0.0$) exhibits the most unusual behavior with very strong rotation at the center. Velocities are referred to the cluster or merger CM.
Fig. 17.— Evolution of the transverse velocity over time for representative shells of the model displayed in Figs. 2 and 3. Shells are $r \in [0, 0.25]$, $r \in [0.75, 1.0]$, $r \in [4.75, 5.0]$, and $r \in [9.75, 10.0]$. After merging ($t \sim 150$ Myr), the average transverse velocity increases over time in the central regions which is the typical signature of the gravogyro instability. On the other hand, it tends to decrease slightly or remain constant in the outer regions. Fluctuations (standard deviation) around the average value in this plot and the following three amount to nearly 40% (error bars are not displayed for clarity).
Fig. 18.— Same as Fig. 17 but for the model with $q = 1.0$, $S_o = 10.0$ pc and $e_o = 0.95$. Here
the long term evolution is similar to that of the single models with $N = 4096$. The average
transverse velocity decreases over time and approaches a constant value. The gravogyro
instability is now absent as expected for a rotating multicomponent model with concurrent
energy equipartition at work.
Fig. 19.— Time evolution of the $z$-component of the specific angular momentum of the model in Figs. 2 and 3. After merging, the remnant exhibits slight decrease of angular momentum.
Fig. 20.— Same as Fig. 19 but for the model with $q = 1.0$, $S_o = 10.0$ pc and $e_o = 0.95$. The evolution is now completely different.
Table 1: Results of the 72 computations after 210 Myr

| $e_0$  | 0.00 | 0.20 | 0.40 | 0.60 | 0.80 | 0.95 |
|--------|------|------|------|------|------|------|
| $S_o$ (pc) | (Myr)/(pc) | (Myr)/(pc) | (Myr)/(pc) | (Myr)/(pc) | (Myr)/(pc) | (Myr)/(pc) |
| (Myr) | (Myr) | (Myr) | (Myr) | (Myr) | (Myr) | (Myr) |

$q = 1.0$

$N_1 = N_2 = 4096, M_{1,2} = 2048M_\odot, R_{vir} = 1$ pc, $R_p = 0.59$ pc, $R_T = 18$ pc

| 10 | $\infty/369$ | $\infty/407$ | $\infty/425$ | $\infty/448$ | $\infty/470$ | $\infty/497$ |
| 46 | 72 | 35 | 28 | 23 | 19 | 17 |

$q = 0.5$

same density

$N_1 = 4096, N_2 = 2048, M_1 = 2048M_\odot, M_2 = 1024M_\odot, R_{vir1} = 1$ pc, $R_{vir2} = 0.79$ pc, $R_{p1} = 0.59$ pc, $R_{p2} = 0.46$ pc, $R_T = 18$ pc

| 10 | 78/0.18 | 64/0.10 | 53/0.55 | 61/0.22 | 59/0.32 | 51/0.17 |
| 53 | 40 | 32 | 26 | 22 | 19 |

$q = 0.5$

different density

$N_1 = 4096, N_2 = 2048, M_1 = 2048M_\odot, M_2 = 1024M_\odot, R_{vir1} = 1$ pc, $R_{vir2} = 0.50$ pc, $R_{p1} = 0.59$ pc, $R_{p2} = 0.29$ pc, $R_T = 18$ pc

| 10 | 78/0.52 | 43/0.38 | 67/0.46 | 56/0.50 | 64/0.40 | 64/0.24 |
| 53 | 40 | 32 | 26 | 22 | 19 |

$q = 0.25$

tidal disruption

$N_1 = 4096, N_2 = 1024, M_1 = 2048M_\odot, M_2 = 512M_\odot, R_{vir1} = 1$ pc, $R_{vir2} = 0.63$ pc, $R_{p1} = 0.59$ pc, $R_{p2} = 0.37$ pc, $R_T = 18$ pc

| 10 | $\infty/134^\dagger$ | $\infty/116$ | $\infty/96$ | $\infty/91$ | $\infty/77$ | $\infty/46$ |
| 58 | 44 | 35 | 29 | 24 | 21 |

$^\dagger$ Merging timescale in Myr / cluster pair spatial separation in pc,

$P_{orb}$ in Myr (Equation 5)

* For models with $q = 0.25$ the separation between the primary cluster and the disrupted secondary is quoted.

$S_o$ is the initial value of the apocluster distance (see the text for details).

$e_0$ is the initial value of the eccentricity.