The dynamical evolution of stellar super-clusters

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Summary

Recent images taken with the Hubble Space Telescope (HST) of the interacting disk galaxies NGC 4038/4039 (the Antennae) reveal clusters of many dozens and possibly hundreds of young compact massive star clusters within projected regions spanning about 100 to 500 pc. It is shown here that a large fraction of the individual star clusters merge within a few tens to a hundred Myr. Bound stellar systems with radii of a few hundred pc, masses \( \lesssim 10^9 \, M_\odot \) and relaxation times of \( 10^{11} - 10^{12} \) yr may form from these. These spheroidal dwarf galaxies contain old stars from the pre-merger galaxy and much younger stars formed in the massive star clusters, and possibly from later gas-accretion events. The possibility that star formation in the outer regions of gas-rich tidal tails may also lead to super clusters is raised. The mass-to-light ratio of these objects is small, because they contain an insignificant amount of dark matter. After many hundred Myr such systems may resemble dwarf spheroidal satellite galaxies with large apparent mass-to-light ratio, if tidal shaping is important.

Subject headings: globular clusters: general – galaxies: interactions – galaxies: kinematics and dynamics – galaxies: star clusters – galaxies: stellar content – Local Group

1. Introduction

In the inner regions of the tidal arms of the interacting galaxy pair NGC 4038/4039, Whitmore & Schweizer (1995) observe with the HST many hundreds of young compact star clusters. Using the re-furbished HST, Whitmore et al. (1998) count thousands of massive star clusters with dimension of a few pc\(^1\). The brightest and bluest of the star clusters are probably younger than 10 Myr. Many hundreds of similar compact star clusters with ages of a few hundred Myr are observed in the merger remnant galaxy NGC 7252 by Miller et al. (1997). The measured luminosity function of these clusters rises steeply with decreasing luminosity, and shows no turnover at the completeness limit. The luminosity function appears to evolve to the form of the old globular clusters as the average nuclear age of the star cluster system increases\(^2\). This is to be expected as a natural consequence of internal dynamical evolution and tidal destruction of the least massive star clusters.

\(^1\)Images are available at [http://oposite.stsci.edu/pubinfo/pr/97/34/]

\(^2\)A compilation by B.C. Whitmore of cluster luminosity functions in mergers of different ages is to be found at [http://oposite.stsci.edu/pubinfo/pr/97/34/images/HistogramsS.GIF]
This impressive observational evidence strongly suggests that globular clusters form in interacting galaxies. The convergent gas flows in colliding gas-rich galaxies lead to localised gas pressures that are very high. Such regions can become gravitationally bound if the gas mass is sufficiently large, favouring the formation and survival of massive clusters (Elmegreen et al. 1993; Elmegreen & Efremov 1997). This is corroborated by the presence of young globular clusters in the Large Magellanic Cloud (LMC), which is interacting mildly with the Milky Way (see e.g. Westerlund 1997). Of special interest in the present context is that some of the LMC clusters appear to form interacting binary systems (e.g. Vallenari, Bettoni & Chiosi 1998). It is thus likely that the compact clusters observed in the Antennae galaxies evolve to globular clusters once the massive stars have faded.

A particular stunning discovery made with the new HST images is that the young compact star clusters are themselves clustered. The super-clusters contain at least a few dozen bright star clusters within a projected region no larger than a few hundred pc, and are centrally concentrated with a core radius of approximately 100 pc or less. Some super-clusters appear to contain hundreds of massive star clusters, with unresolved central regions. It is interesting to note that some super-clusters also appear to be clustered in groups of a few.

The aim of this paper is to investigate the likely fate of such super-clusters, and their possible relationship to spheroidal dwarf galaxies. Also, the dynamical evolution of globular clusters in spheroidal dwarf galaxies subject to tidal damage is briefly discussed. The dynamical state of the super-clusters is considered in Section 2, and Section 3 contains an estimate of their stellar populations. N-body simulations from the literature, which are described in Section 4, are applied to this problem in Section 5. The results are discussed in Section 6, and the conclusions are given in Section 7.

2. Dynamical Stability

The new HST images suggest that most of the gas has already been cleared from the visible super-clusters. Only few of the compact star clusters that are within the super-clusters appear reddened. Whitmore & Schweizer (1995) estimate that only about 0.1 Myr are required for a region of radius 10 pc to be cleared from gas and dust. If gas expulsion had unbound the compact star clusters then they should disperse within roughly one crossing time, which is less than 1 Myr for a star cluster containing $\gtrsim 10^5$ stars within a few pc, implying a velocity dispersion of about 10 pc/Myr. Since most of the star clusters are older than 5 Myr (Whitmore & Schweizer 1995) and are still $< 10$ pc in extend, it follows that they are most probably bound objects.

The time-scale for evaporation of the compact clusters due to internal dynamical evolution is at least 1 Gyr, while it is longer than a Hubble time for typical globular clusters. Stars more massive than $8 M_\odot$ are lost from the cluster through supernova explosions within about 50 Myr. Their loss will not unbind the cluster because they contribute only about 6-10 per cent of the cluster mass for a solar neighbourhood stellar mass function (see below). Stars more massive than $2 M_\odot$ evolve off the main sequence with significant mass loss within about 500 Myr. They contribute about 25 per cent to the cluster mass, so that their loss will also not unbind the cluster.

It is unlikely that the compact star clusters comprising the super-clusters fly apart owing to a large internal velocity dispersion. If the groups of clusters were unbound and expanding with velocities typical for the stellar kinematics of the parent galaxy (i.e. roughly 30 pc/Myr) then, given their ages of roughly 10 Myr, they ought to be either much more dispersed than they are (600 pc in diameter), or they would
have had to be formed in a point-like region containing the entire mass of the super-cluster in order to have the dimensions observed now. Both appear unlikely, especially since there are at least about ten super-clusters with similar extensions visible at different locations in the images.

The brightest individual compact star clusters imaged by Whitmore et al. (1998) and Whitmore & Schweizer (1995) have an integrated absolute V-band magnitude of $M_{V,cl} \approx -15$. A lower limit cannot at present be determined, but the luminosity function of the young star clusters is a power-law, $\phi \propto L^{-1.78 \pm 0.05}$ (Whitmore & Schweizer 1995), where $L$ is the integrated luminosity of an individual cluster, and $dL$ is the number of clusters in the luminosity range $L$ to $L + dL$. The luminosity function shows no turnover down to the completeness limit of $M_{V,cl} \approx 10$.

An O-type star with a mass of $m = 40 M_\odot$ has $M_V \approx -5.6$, so that the above range on $M_{V,cl}$ roughly corresponds to clusters of 5800 O stars down to 58 O stars. If the initial mass function is similar to what is seen in the solar neighbourhood (Scalo 1986 for $m \gtrsim 1 M_\odot$; Kroupa, Tout & Gilmore 1993 for $m \lesssim 1 M_\odot$), then each O star is associated with roughly 2300 stars less massive than $1 M_\odot$. The star clusters then consist of roughly $1.3 \times 10^7$ down to $1.3 \times 10^5$ stars, which corresponds to cluster masses in the range $10^5 M_\odot$ down to $10^5 M_\odot$ for a mean stellar mass of $m = 0.5 M_\odot$.

A super-cluster containing tens or hundreds of such clusters can thus have a total mass of $M_{scl} \approx 10^6 - 10^9 M_\odot$. This mass is contained within a projected region with radius of roughly 200 pc. The tidal radius is $r_t \approx [M_{scl}/(3 M_{gal})]^{1/3} R$ (Binney & Tremaine 1987), where $M_{gal}$ is the mass of the galaxy within the distance $R$ of the super-cluster from the centre of the galaxy. The super-clusters lie at a distance of typically $R \approx 5$ kpc from the centre of NGC 4038 in the Antennae. The tidal radius is thus $r_t \approx 90 - 900$ pc if $M_{gal} \approx 6 \times 10^{10} M_\odot$, which is the mass within 5 kpc of a disk galaxy with a circular velocity of 220 km/s. This estimate of $r_t$ can only serve as a guide because the galactic mass distribution within $R$ is highly uncertain given the seriously perturbed state of both interacting galaxies.

The most massive super-clusters should thus be stable against tidal disruption. The less massive ones will stretch along their orbits leading to families of massive star clusters on very similar galactic orbits.

3. Stellar Population

There is no evidence for significant amounts of dark matter distributed like the disk in the Galaxy (Gilmore, Wyse & Kuijken 1989; Kuijken 1991). Assuming the disks of the unperturbed galaxies that now form the interacting pair in the Antennae were similar to the Galactic disk, which is supported by the analysis of the mass-to-light ratio and global stability of galactic disks by Syer, Mao & Mo (1998), it follows that the dark-matter content of the super-clusters is insignificant: Only an insignificant amount of dark halo matter will become bound to the super-clusters because it has a velocity dispersion of the order of 100 km/s. This is explicitly shown in the simulations of interacting galaxies leading to the probable formation of tidal-tail dwarf galaxies (Barnes & Hernquist 1992).

The super-clusters cover a spherical volume of about $3 \times 10^7$ pc$^3$ for a radius of 200 pc. Assuming a stellar number density of 0.1 stars pc$^{-3}$, which is characteristic for the solar neighbourhood, it follows that the volume should contain of the order of $10^6 - 10^7$ disk stars. Not all stars in this volume will remain bound to the super-cluster. The escape velocity, $v_{esc} = (2GM_{scl}/r)^{1/2}$ (gravitational constant $G = 4.49 \times 10^{-15}$ pc$^3$/(M$_\odot$ yr$^2$)) from a super-cluster with a mass $M_{scl} = 10^6 - 10^9 M_\odot$ within a radius $r = 200$ pc is, for stars within that radius, $v_{esc} \approx 7 - 200$ km/s. Assuming the velocity dispersion is
\( \sigma^* = 30 \text{ km/s} \) (similar to what is observed in the solar neighbourhood), and approximating the distribution of velocities by a Gaussian function (Reid, Hawley & Gizis 1995), about 13 (99) per cent of the stars have velocities relative to the local standard of rest of less than 5 (78) km/s. Thus, it is likely that about \( 10^5 - 10^7 \) stars in the respective volume will remain bound to the super-cluster, if the super-cluster moves with the local standard of rest, and if the super-cluster forms on a time-scale that is shorter than the crossing time \( t_{cr} = 2r/\sigma^* \approx 13 \text{ Myr} \), so that the velocities of the older disc stars have no time to adjust to the deeper potential well. In the super-cluster, the proportion of bound old to new stars may then approach a few tens per cent. If, on the other hand, the super-clusters form on a time-scale that is longer than \( t_{cr} \), then the disk stars near the forming super cluster will accelerate into the potential well, subsequently leaving it.

The older disc stars formed throughout the galaxy over its entire age until the time of the formation of the super-clusters. The stellar population in a super-cluster is therefore a mixture of stars formed in the process of cluster formation and of stars belonging to the galactic disk prior to the galaxy interaction. The age and metallicity distribution of the stars in super-clusters should thus be complex, and some radial age and metallicity gradients are expected because the older, metal deficient stars are less concentrated towards the centre of the super-clusters.

4. N-body Simulations

The crossing time of a super-cluster with diameter \( d \) is approximately \( t_{\text{cross}} = d/\sigma \), where \( \sigma \approx (GM_{\text{sc1}}/d)^{1/2} \) is the velocity dispersion in a spherical system in virial equilibrium. For \( M_{\text{sc1}} = 10^6 - 10^9 \text{ M}_\odot \) and \( d = 400 \text{ pc} \), it follows that \( \sigma \approx 3 - 100 \text{ pc/Myr} \) and \( t_{\text{cross}} \approx 130 - 4 \text{ Myr} \).

The time-scale for cluster-cluster interactions is therefore comparable to or longer than the present age of the young clusters (\(< 10 \text{ Myr} \)), and significantly shorter than the half-mass relaxation time, \( t_{\text{rh}}(\mathbb{M}) \approx 1 \text{ Gyr} \), typical for the individual massive star clusters.

Core collapse occurs within \( 2t_{\text{rh}}(\mathbb{M}) - 3t_{\text{rh}}(\mathbb{M}) \) for a cluster with a realistic stellar mass function (Spitzer 1987; Inagaki 1985; Inagaki & Saslaw 1985). However, massive stars with mass \( m_m \) will segregate towards the cluster core on the equipartition time-scale, \( t_{\text{eq}} \approx (m/\mathbb{M}) t_{\text{rh}} \), if initially there is no mass-segregation and stellar velocities are independent of mass (Spitzer 1987, p.74). Under these conditions, and if \( m_m \approx 100 \mathbb{M} \), some internal dynamical evolution will result within 10 Myr. However, observations of young embedded clusters show that the most massive stars are usually located at the cluster centre, so that the stellar system will evolve on a time-scale longer than \( t_{\text{eq}} \). For the present purpose, the internal dynamical evolution of the individual star clusters through two-body relaxation can thus be neglected over the dynamical evolution time-scale of the super-clusters. Furthermore, the thousands of O type stars within the super-clusters have swept out most of the remaining gas within less than about 10 Myr (Section 2).

Collision-less simulations without gas of a super-cluster can thus be performed to study its dynamical evolution on a time-scale that is smaller than the relaxation time within an individual globular star cluster. Such simulations exist in the literature. Garijo, Athanassoula & García-Goméz (1997, hereinafter GAG) report simulations of clusters of 50 galaxies in order to investigate the formation of centrally dominant galaxies.
4.1. Scaling the problem

The simulations of GAG can be applied to the problem here by scaling to the appropriate mass and length scales. This means that the tidal field of the merging galaxies is ignored. This is a reasonable simplification in this pilot study in which the structural and kinematical properties of an evolved super-cluster are to be quantified. A tidal field will be added in more detailed investigations (Fellhauer & Kroupa 1998).

The freedom of scale in the gravitational problem is expounded nicely by Madejsky & Bien (1993). The transformation equation between two systems of units is \((L/L^*)^3 = (T/T^*)^2(M/M^*)\) (their equation 1; \(L = \) length, \(T = \) time and \(M = \) mass). Velocities scale as \(V/V^* = (L/T)(T^*/L^*)\). The length-scale in the galaxy simulations of GAG is defined by the Plummer radius of each galaxy, \(L^* = 6 \) kpc, and the mass-scale is defined by the mass of an individual galaxy, \(M^* = 5 \times 10^{11} M_\odot\). The unit of time in their simulations is \(T^* = 140 \) Myr. For the problem of interest here, the Plummer radius of each star cluster is \(L = 6 \) pc, the star-cluster mass is \(M = 10^6 M_\odot\) and the resulting unit of time is \(T = 3.1 \) Myr. Thus, a length of 100 kpc and a time-span of 1 Gyr in the galaxy problem of GAG corresponds to a length of 100 pc and a time-span of 22 Myr in the super-cluster problem studied here. Finally, a velocity of \(V^* = 100 \) km/s in their simulations corresponds to \(V = 4.5 \) km/s in the super-cluster problem here.

4.2. Initial conditions

In the simulations of GAG the galaxies are initially represented as identical Plummer spheres, each consisting of 900 particles. They perform eight simulations using a tree-code adapted for a Cray computer. The softening length is 1.5 pc in the units used here, and the simulations are run for 4000 steps, i.e. 95 Myr in the units used here.

The initial conditions are varied to give seven different configurations of interest here (the eighth is the hollow configuration in which there are no galaxies in the central region of the galaxy cluster). These are summarised in table 1 of GAG. In the following, a globular cluster is meant to mean a galaxy in their simulations. The distance of each of the 50 globular clusters to the centre of the super-cluster is chosen randomly between 0 and \(r_{\text{scl}}\). Four simulations with an outer radius of the super-cluster of \(r_{\text{scl}} = 900 \) pc are run for initially collapsing super-clusters with initially spherical, oblate and prolate shapes. Initially spherical super-clusters in virial equilibrium are also simulated for \(r_{\text{scl}} = 600 \) pc and 300 pc. The latter are referred to as the “compact models”.

5. Dynamical Evolution

In all cases the globular clusters initially near the centre of the super-clusters merge within a few \(10^7 \) yr. Thereafter, individual globular clusters continue to merge with the growing central stellar system. Mass is also lost from the globular clusters through mutual tidal forces, which leads to an extended stellar component occupying the entire spherical volume within roughly \(r_{\text{scl}}\). Some particles escape. The configuration at the start of the simulation with \(r_{\text{scl}} = 600 \) pc and after 95 Myr is shown in Fig. 1. Additional time-steps are displayed in fig. 1 of GAG.

The number of globular clusters decreases with time at different rates depending on the initial configuration. After 95 Myr less than 60 per cent of the initial number of globular clusters remain in all
Fig. 1.— Two snap-shots from simulation V of GAG. Initially (upper panel), the super-cluster is in virial equilibrium. Some of the clusters expand outwards because they have positive radial velocities initially. The lower panel shows the resultant system after 95 Myr.
seven simulations. The cold collapse models and the compact models lead to a survival fraction of 40 per cent by this time. In the cold collapse models, the mean radius of the surviving globular cluster system decays but stabilises by about 62 Myr at the value of roughly 300 pc. In the super-clusters that are initially in virial equilibrium, the mean radius increases to 700-900 pc after 95 Myr (fig. 2 in GAG), because the clusters on low-eccentricity and long-period orbits survive preferentially.

The mean velocity dispersion in the central object remains roughly constant after about 40 Myr, and is determined by the initial concentration, i.e. $r_{scl}$. The velocity dispersion ranges between 14 and 18 km/s.

Further details concerning the rate of growth of the mass of the central stellar system, of its mean radius and the evolution of the surviving globular clusters, of the axial ratio of the central stellar system, of its density and velocity dispersion profiles can be found in GAG.

The main interest here lies in the overall properties of the merged super-cluster. Between about 40 and 60 per cent of the globular clusters survive for 95 Myr. By this time, the centrally formed objects have, approximately, three-dimensional Hernquist profiles with half-mass radii in the range $r_{1/2} = 45$ to 55 pc for the super-clusters initially in virial equilibrium, and $r_{1/2} = 73$ to 92 pc for the initially collapsing super-clusters (García-Gómez, private communication). Evolution of the half-mass radius is slow, and it will not increase significantly after 100 Myr. At 95 Myr, the centrally formed object has a projected surface density profile that is flat within roughly the innermost 20 pc. Further out, the surface density profile decreases with radius and approximately follows a $r^{1/4}$ law with deviations that depend on the initial configuration (figs. 16-18 in GAG). The projected velocity dispersion profile is flat within the innermost 20 pc, and decreases roughly as a power-law with increasing radius (fig. 20 in GAG). No significant further evolution of these quantities is expected after 100 Myr. Clearly, a time-dependent tidal field will alter both the three- and two-dimensional density profiles.

6. Discussion

All initial conditions discussed here lead within 100 Myr to a central object that has a half-mass radius of about 45–95 pc and consists of about $10^8$ stars, and of surviving globular clusters on low-eccentricity, long-period orbits. The tidal radius would be, in the case of the Antennae, about 300 pc (Section 2), so that tidal shaping of the central object must be expected (Oh, Lin & Aarseth 1995). The relaxation time (see Binney & Tremaine 1987) of this merged object is roughly $2 - 15 \times 10^{11}$ yr, taking for the mean stellar mass $\mu = 0.5 M_\odot$ and for the number of stars $10^7 - 10^8$. Practically, it is a collision-less system, and can be called a dwarf galaxy. It is spheroidal. Deviations from spherical symmetry, and the density profile, are determined by the initial conditions as demonstrated by GAG, and by the tidal field (Fellhauer & Kroupa 1998).

Hereinafter such objects are referred to as spherical dwarf galaxies, to distinguish them from the well-known dwarf-spheroidal (dSph) and dwarf-elliptical (dE) galaxies. Spheroidal dwarf galaxies are thus postulated to evolve from massive super clusters. They have not been knowingly observationally identified yet.

However, the evolution of such a system at times longer than a few hundred Myr is interesting in the context of dE galaxies with nuclei, and dSph satellites with globular clusters. A rough estimate of the dynamical friction time, $t_{dynfr}$ (see e.g. Binney & Tremaine 1987), for a globular cluster with a mass of $10^5 M_\odot$ in a spheroidal dwarf galaxy with a mass of $5 \times 10^7 M_\odot$, suggests that a surviving cluster can sink
to the centre within a few Gyr. The accumulation of one or a few globular clusters at the centre of such a stellar system should lead to a spheroidal dwarf galaxy with a nucleus.

Future survival of the dwarf galaxy depends on its mass and its orbit within the merging galaxy. Those not massive enough will fall apart in the tidal field, contributing families of globular clusters on very similar orbits. The present configuration of the Antennae suggest that approximately 200 Myr have passed since the first pericenter passage (Barnes 1988). The two galaxies will probably suffer a second pericenter passage within a few hundred Myr, and will ultimately merge when additional long tidal arms are flung out (Mihos, Dubinski & Hernquist 1998). The massive spheroidal dwarf galaxies formed now may be ejected onto eccentric orbits with apo-galactica of tens of kpc and orbital periods of the order of a Gyr. The final merged 'Antennae' galaxy may evolve to an early-type disk galaxy after the ejected gas re-settles in one plane (Hibbard & Mihos 1995, Combes 1998), but evolution to an elliptical galaxy is also possible.

The overall rate of sinking of globular clusters towards the centre of the dwarf galaxy can be slowed if it looses stars in a tidal field. Near each peri-galacticon, the dwarf is heated and expands as a result of mass loss. Any remaining globular clusters will then find themselves at larger distances from the dwarf’s centre, with $t_{\text{dynfr}}$ lengthened because of the dwarf’s reduced mass and density. The net result may thus be that globular clusters sink towards the centre of a spheroidal dwarf galaxy increasing their robustness against tidal removal from the dwarf. Mass loss near peri-galacticon then essentially resets the dynamical friction clock by leading to a general expansion of the dwarf. Thereafter the clock ticks at a slower rate, and some clusters may never reach the centre of the dwarf galaxy.

Viewed from this perspective, it is interesting to note that remnants of globular clusters may be discernible as small-scale sub-structure or as nuclei in dSph galaxies. The search for remnants of star clusters in Galactic dSph satellites is difficult though because some of them show significant sub-structure (Demers et al 1995; Irwin & Hatzidimitriou 1995). However, Ursa Minor contains a density enhancement near its centre. This could be the remnant of a globular cluster. Also, Fornax contains five globular clusters.

If a dwarf galaxy accretes a gas cloud that is on a similar orbit then an additional period of star formation may take place within the dwarf. If this were to occur then the gas is funnelled to the central regions of the dwarf, possibly adding to or creating a nucleus (van den Bergh 1986). The resultant age and metallicity distribution of the stars may thus show similarities to the observed distributions in Galactic dSph satellites (see also Section 3). These are reviewed by Ferguson & Binggeli (1994), Gallagher & Wyse (1994), Grebel (1997) and Da Costa (1997).

High-resolution imaging should show if the formation of super-clusters is also a mode of star-formation in outer tidal arms. That dwarf galaxies may form in tidal tails has been surmised for some time (e.g. Lynden-Bell 1976). Evidence for this is reviewed by Duc & Mirabel (1998) and Kroupa (1998a). It is unclear though if such gas-rich objects survive the star-formation episode as bound entities, nor if they are sufficiently stable against tidal field destruction to survive many orbits (see Kroupa 1998b). If rich groups of globular clusters form in these then, as shown here, bound spheroidal dwarf galaxies may remain after gas expulsion, adding to the faint end of the galaxy luminosity function. Such tidal-dwarf galaxies are void of dark matter, but may appear to be dark-matter dominated after significant tidal shaping (Kroupa 1997; Klessen & Kroupa 1998). These issues are of relevance to the epoch of galaxy construction. If most spiral galaxies formed at a red-shift of $1 \lesssim z \lesssim 2$ from merging gas-rich sub-structures (e.g. Driver et al. 1998) in which some super clusters are formed, then today’s larger galaxies might naturally end up with systems of spheroidal satellite galaxies.
7. Conclusions

The clusters of many dozens and hundreds of massive star clusters imaged in the inner parts of the tidal arms in the Antennae evolve on a time-scale that is comparable to or somewhat longer than the present age of the super-clusters, but significantly shorter than the half-mass relaxation time of the individual massive star clusters. The evolution may be approximated using a collision-less method, and leads to the formation of a central stellar system that is more extended than the individual star clusters by one to two orders of magnitude. It has a mass of roughly $10^6 - 10^9 \, M_\odot$, depending on how populous the super-cluster was, and consists of stars formed during the formation of the super-cluster and of old stars from the parent galaxy, leading to radial metallicity and age gradients within the object. Its relaxation time is $10^{11} - 10^{12} \, \text{yr}$, so that it may be called a spheroidal dwarf galaxy. It contains essentially no dark matter apart from stellar remnants.

Tidal stability of the most massive young dwarf galaxies is likely, but tidal modification at birth will be important. If the dwarf galaxy formed in the inner parts of a tidal arm during or after the first galaxy–galaxy encounter, then it is feasible that it may be ejected during the final merging encounter onto an eccentric orbit with an apo-centric distance of tens of kpc. The dwarf galaxy will subsequently evolve through periodic tidal modification and may appear similar to some of the Galactic dSph satellites.

Since not all of the massive star clusters originally in the super-cluster merge within the first few hundred Myr, and since they are expected to evolve to globular clusters, it follows that some of the more massive spheroidal dwarfs may contain a few globular clusters, a few of which may sink to their centres contributing to or producing a nucleus. Tidally induced mass loss from the dwarf, however, may compensate orbital shrinkage through dynamical friction. In this case, some globular clusters may remain bound to the dwarf without reaching its centre. The globular clusters are younger than the oldest stars in the dwarf. Those stripped from the dwarf will remain members of the tidal stream. Super clusters not massive enough to remain bound in the tidal field will disassemble, producing families of globular clusters on similar orbits.

The formation of stellar super-clusters may be an important mode of star formation during galaxy assembly at $1 \lesssim z \lesssim 2$, and at $z \approx 0$ in tidal-tail dwarf galaxies which condense on highly eccentric orbits at distances of many tens of kpc from the parent galaxies. Such dwarfs are distinct from dwarf galaxies that formed from the Hubble flow in that they contain essentially no dark matter.

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