Star clusters: basic galactic building blocks
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Star cluster dynamics in galaxies

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Abstract. I present a review of star cluster (SC) dynamics in galaxies, with special emphasis on the effects of global galactic dynamics on SC formation and evolution. I particularly discuss (i) dynamical friction processes affecting SCs in galaxies of different masses, (ii) formation of stellar galactic nuclei and massive globular clusters (GCs) through multiple merging of SCs, (iii) interactions between giant molecular clouds (GMCs) and SCs, (iv) SC destruction due to the strong tidal fields in galaxy mergers and (v) the formation of low-mass dwarfs from numerous SCs. I also discuss some recent observational results on SC mass functions in dwarf galaxies and physical properties of GC systems in luminous galaxies based on recent results of numerical simulations of SC dynamics in galaxies.

Keywords. globular clusters: general, open clusters and associations: general, galaxies: formation, galaxies: evolution

1. Introduction

The formation and evolution of star clusters (SCs) can be strongly influenced by the global dynamics of their host galaxies, such as by their strong tidal fields (e.g., Vesperini 2000; Baumgardt & Makino 2003), collisions between low-mass SCs and GMCs (e.g., Gieles *et al.* 2006) and dissipative gas dynamics (e.g., Bekki *et al.* 2002; Bournaud *et al.* 2008). Equally, basic galactic components such as stellar galactic nuclei and thin and thick disks can also be influenced dynamically by the evolution of SC systems (e.g., Kroupa 1998; Capuzzo–Dolcetta & Vicari 2005). Radial density profiles of the stars in individual SCs formed from GMCs may depend on the strength of the tidal field of their host galaxy (e.g., Hurley & Bekki 2008). Furthermore, mass functions (MFs) of old GCs and radial density profiles of GC systems (GCSs) in galaxies can be significantly changed owing to destruction of GCs with different masses within galaxies (e.g., Vesperini 2000).

Here, I focus on how the formation and evolution of SCs and SC systems (SCSs) in galaxies can be influenced by global dynamical processes. I do not intend to discuss *internal stellar dynamics of SCs*, mainly because a number of contributions at this conference (e.g., Boily, these proceedings) focus on internal SC evolution. I select five key topics and describe observational backgrounds, unresolved problems, results of previous theoretical studies and implications of the latest theoretical results. SCs in galaxy-scale simulations are usually represented by point-mass particles, so that internal evolution cannot be investigated properly (e.g., Fujii *et al.* 2008). I briefly discuss how to construct more self-consistent models for SC evolution in galaxies, based on more sophisticated numerical simulations.

2. Dynamical friction of SCs in galaxies

Tremaine *et al.* (1975) were among the first to discuss dynamical friction (DF) of massive GCs in galactic halos in the context of the formation of stellar galactic nuclei.

The timescale of DF ($t_{\rm fric}$) for typical GCs with masses ($M_{\rm gc}$) of $2\times10^5\,{\rm M}_\odot$ within galactic halos of luminous galaxies is, however, quite long (e.g., Binney & Tremaine 1987). For the Galaxy, with a circular velocity $v_{\rm c}$ = 220 km s^{-1} and Coulomb logarithm $\ln\Lambda = 10$, $t_{\rm fric}$ can be estimated as

$$t_{\rm fric} = 1.2\times10^{11}\left(\frac{r_{\rm i}}{2\,{\rm kpc}}\right)^2\left(\frac{v_{\rm c}}{220{\rm km\,s^{-1}}}\right)\left(\frac{M_{\rm gc}}{2\times10^5{\rm M}_\odot}\right)^{-1}{\rm yr}, \tag{2.1}$$

where $r_{\rm i}$ is the distance of a given GC from the center of its host galaxy. For a galaxy with $v_{\rm c}$ = 70 km s^{-1} and $\ln\Lambda = 10$,

$$t_{\rm fric} = 1.8\times10^{9}\left(\frac{r_{\rm i}}{1\,{\rm kpc}}\right)^2\left(\frac{v_{\rm c}}{70{\rm km\,s^{-1}}}\right)\left(\frac{M_{\rm gc}}{10^6{\rm M}_\odot}\right)^{-1}{\rm yr}. \tag{2.2}$$

Therefore, although DF cannot be important for the evolution of normal SCs and GCs within luminous galaxies like the Milky Way, it can significantly change the physical properties of SCs and SCSs in dwarf galaxies. For example, DF of SCs in the central regions of dwarf galaxies can be a key determinant for their transformation from nonnucleated to nucleated dwarf galaxies (e.g., Oh & Lin 2000; Bekki *et al.* 2004).

Recent theoretical studies have shown that the details of DF processes can be determined by the mass distributions of their host galaxies, such as by their dark-matter halos (e.g., Hernandez & Gilmore 1998; Goerdt *et al.* 2006; Inoue 2009). Orbital decay of GCs due to DF can significantly change the spatial distribution of GCs and thus increase their susceptibility to being destroyed by strong galactic tidal fields (e.g., Vesperini 2000). Although these previous studies contributed significantly to a better understanding of SC evolution within galaxies due to DF, their models are not fully self-consistent in the sense that they investigated DF of SCs *in galactic halos* but they did not include DF *caused by field stars in galactic bulges and disks*. Given that DF can depend strongly on the relative velocities between SCs and background components, SC DF can be quite

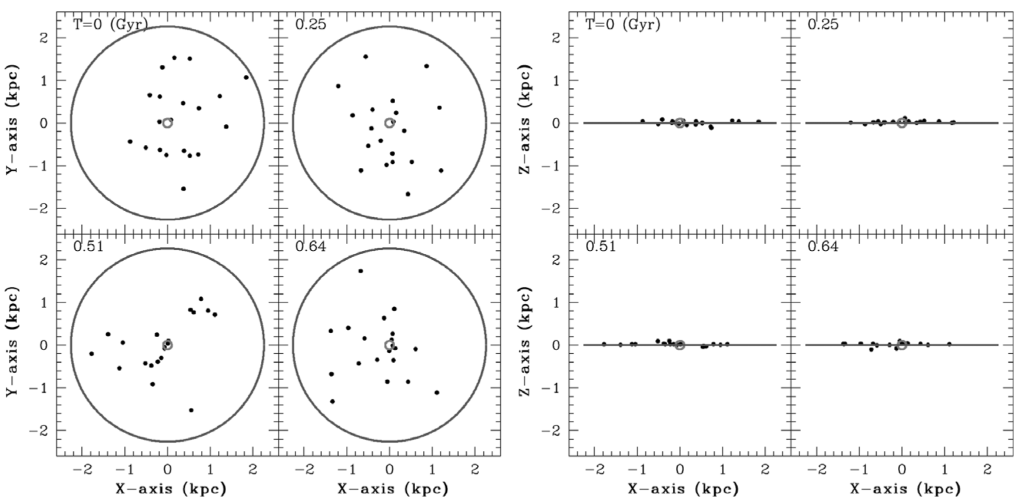

Figure 1. Spatial distributions of disk SCs (small black dots) in a disk galaxy for four different time steps in a model with $M_{\rm disk} = 10^9\,{\rm M}_\odot$. The left- and right-hand panels show the distributions of SCs projected onto the x–y and x–z planes, respectively. Time (T) in units of Gyr is given in each of the four panels. Large blue and small red circles represent the initial disk size of the galaxy and the nuclear region (R = 100 pc), respectively.

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efficient in disk galaxies, where the relative velocities between SCs and disk field stars can be rather small.

Thus, here I discuss DF of SCs owing to disk field stars, based on the latest results of numerical simulations (primarily our own) of SC evolution due to DF within disk galaxies. DF processes of SCs caused by field stars in disk galaxies are important, first because recent cosmological hydrodynamical simulations of the possible formation sites of the first GCs (Kravtsov & Gnedin 2005) have shown that the present-day GCs can be formed within disk galaxies at high redshifts ($z \sim 3$), second because less luminous disk galaxies like the Large Magellanic Cloud (LMC) have disky GC systems in which the GCs have disky spatial distributions and rotational kinematics (e.g., Freeman *et al.* 1983; Olsen *et al.* 2004), and third because previous theoretical studies suggested that the present-day dwarf ellipticals (dEs) were previously less luminous disk galaxies with no or small bulges (Mastropietro *et al.* 2004). Therefore, DF of SCs due to disk field stars can be important for the evolution of the luminosity function (LFs) and MFs of SCs and GCs in dEs and the structural and kinematic properties of GCSs in less luminous disk galaxies.

Figure 1 shows the time evolution of the projected SCS distribution, composed of 20 SCs in a disk galaxy with an initial disk size ($R_{\rm disk}$) of 2.3 kpc and initial disk and halo masses ($M_{\rm disk}$ and $M_{\rm halo}$, respectively) of 10^9 and $10^{10}{\rm M}_\odot$, respectively. The canonical

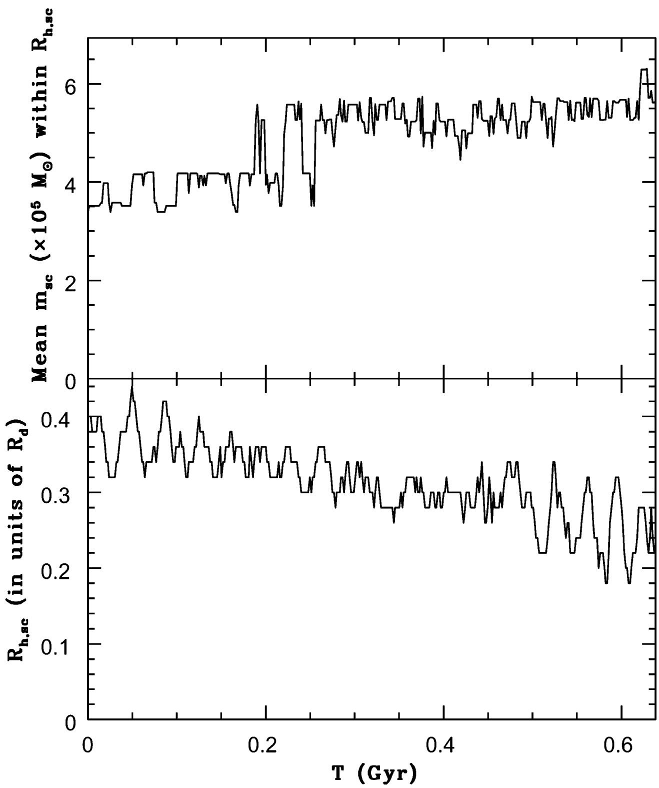

Figure 2. Time evolution of the half-number radius ($R_{\rm h,sc}$) of the SCS in a disk galaxy with $M_{\rm disk} = 10^9{\rm M}_\odot$ *(bottom)* and the mean SC mass within $R_{\rm h,sc}$ *(top)*. Note that both $R_{\rm h,sc}$ and the mean $m_{\rm sc}$ can change rapidly owing to orbital decay of SCs caused by DF, within much less than 1 Gyr.

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MF of Galactic GCs (Harris 1991) is used for these SCs,

$$\Phi(M) \propto e^{-(M-M_0)^2/2\sigma_{\rm m}^2}, \tag{2.3}$$

where $M_0(V) = -7.23 \pm 0.23$ mag and $\sigma_{\rm m}$=1.25 mag. The minimum and maximum SC masses are set at 7×10^4 and $2 \times 10^6 {\rm M}_\odot$, respectively, for a reasonable mass-to-light (M/L) ratio (the details of the model are given in Bekki 2009). The SC models discussed in Sections 3 through 6 are the same. The SCs can be influenced not only by DF caused by disk field stars but also by the global dynamical action of spiral arms and bars in the disk. It is clear from Figure 1 that several massive SCs can pass through the nuclear region ($R \leqslant 100$ pc) at $T = 0.51$ Gyr and later, owing to orbital decay of these SCs caused by DF due to field stars in the disk galaxy. In this model, 30% of the SCs (6 out of 20) can be transferred to the nuclear region within 0.64 Gyr by DF.

Figure 2 shows that the half-number radius of the SCS ($R_{\rm h,sc}$) evolves from $0.38R_{\rm disk}$ (corresponding to = 0.86 kpc) to $0.30R_{\rm disk}$ (0.68 kpc) in 0.6 Gyr. The mean of the SC masses within $R_{\rm h,sc}$ becomes higher because DF is more efficient for more massive SCs: the number fraction of more massive SCs within $R_{\rm h,sc}$ becomes larger owing to the more rapid radial transfer of more massive SCs to the inner regions of the disk. The total number of SCs within $0.1R_{\rm disk}$ gradually increases, so that a multiple-SC system with a total mass of $4.3 \times 10^6 {\rm M}_\odot$ can form in the nuclear region of the disk. The x, y and z components of the velocity dispersions of the multiple SCs are 17.7, 23.6 and 3.2 km s^{-1}, respectively. As these velocity dispersions are comparable to the internal velocity

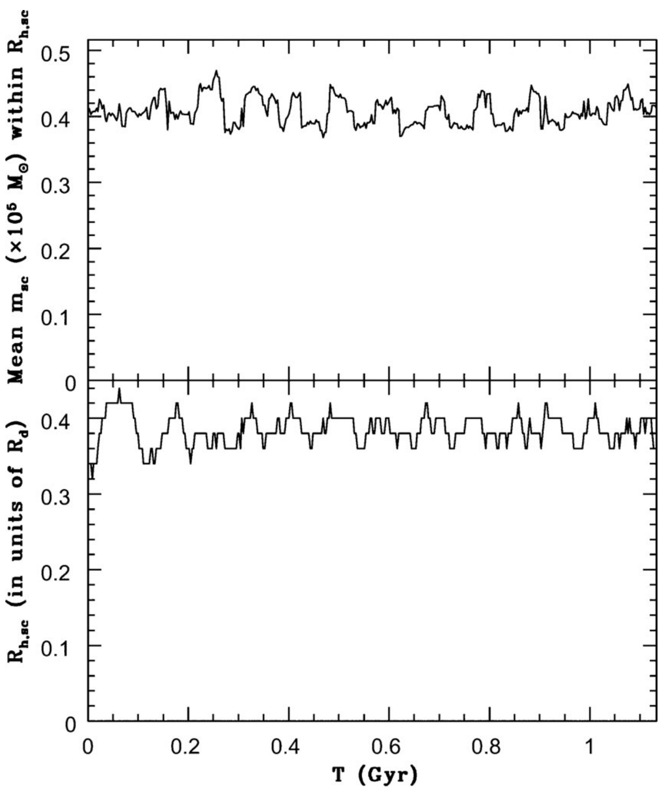

Figure 3. As Figure 2, but for a disk model with $M_{\rm disk} = 10^{10}{\rm M}_\odot$. Note that $R_{\rm h,sc}$ and the mean $m_{\rm sc}$ within $R_{\rm h,sc}$ in this high-mass disk model show little change in their time evolution in comparison with the low-mass disk simulation.

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dispersions of the nuclear massive SCs, this suggests that the nuclear SCs may soon merge to form a single nucleus.

Thus, the timescale for DF of SCs in less luminous disk galaxies is rather short (less than 1 Gyr), so that DF can significantly change (i) the LFs and MFs of SCs and GCs and (ii) the structural and kinematic properties of SCSs and GCSs in these disk galaxies. One of the implications of these results is that the LFs and MFs of SCs and GCs can steepen owing to the consumption of more massive clusters in nuclear regions of galaxies (i.e., inward transfer and the resulting formation of stellar nuclei, which cannot be identified as a SC or GC). However, it should be stressed here that DF cannot be important for the evolution of SCSs in more luminous disk galaxies with $M_{\rm disk} \geqslant 10^{10}{\rm M}_{\odot}$. Figure 3 shows that neither $R_{\rm h,sc}$ nor the mean $m_{\rm sc}$ within $R_{\rm h,sc}$ evolve significantly with time for a disk galaxy with $M_{\rm disk} = 10^{10}{\rm M}_{\odot}$. For this more massive disk galaxy, DF cannot be effective within a few Gyr, not even for SCs with $m_{\rm sc} \sim 10^{6}{\rm M}_{\odot}$, so that the radial number-density profile of the SCS cannot change. The reason for this less effective DF is that relative velocities between disk field stars and SCs are so large that DF cannot work for these more massive disk galaxies. The results in Figures 3 and 4 thus imply that (i) DF affecting SCs in disk galaxies can only be effective in dwarf galaxies and thus (ii) the LFs and MFs of GCs can steepen more significantly due to DF in less luminous galaxies, as observed in dwarf galaxies (e.g., Jordán *et al.* 2006).

3. Formation of stellar galactic nuclei trough SC merging

Previous theoretical studies discussed the formation of stellar galactic nuclei through mergers of SCs (or GCs) in galaxies with different physical properties (e.g., Lotz *et al.* 2001; Capuzzo–Dolcetta & Vicari 2005). Recent, fully self-consistent N-body simulations have shown that mergers of SCs in the inner regions of galaxies lead to the formation of stellar galactic nuclei with projected radial density profiles similar to what is observed (e.g., Capuzzo–Dolcetta & Miocchi 2008). One of the remaining questions in the SC-merger scenario of nucleus formation is whether it can explain the observed relation between the masses of stellar nuclei and those of their host galaxies ($M_{\rm nuc} \sim 0.003 M_{\rm gal}$, where $M_{\rm gal}$ is the galaxy mass; Côté *et al.* 2006). Since the observational study of Côté

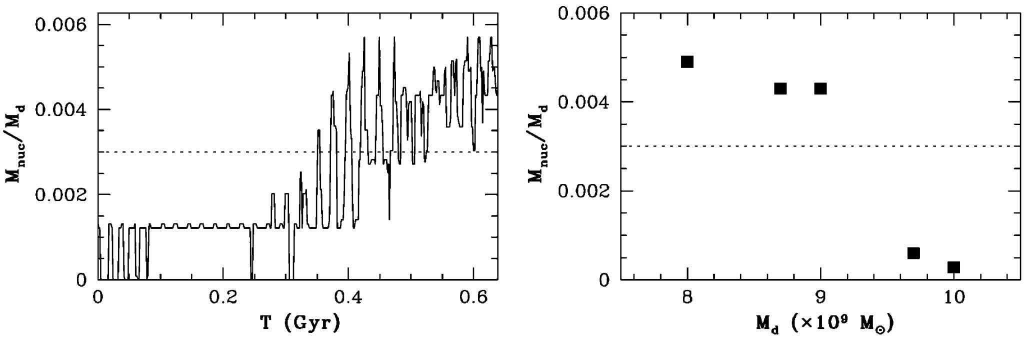

Figure 4. Time evolution of the nuclear mass ratio ($M_{\rm nuc}/M_{\rm disk}$) for a disk model with $M_{\rm disk} = 10^{9}{\rm M}_{\odot}$ *(left)* and as a function of disk mass, $M_{\rm disk}$. For both panels, the observed nuclear mass ratio (i.e., $M_{\rm nuc}/M_{\rm disk} = 0.003$) is indicated by a dotted line, for comparison. In this galaxy-scale simulation, the nuclear SCs are assumed to merge quickly and form a single stellar nucleus (Bekki *et al.* 2004). Therefore, $M_{\rm nuc}$ is assumed to be the total mass of SCs within the nuclear region of the galaxy; it is not literally the total mass of a single stellar nucleus. Thus, $M_{\rm nuc}/M_{\rm disk}$ can increase and decrease with time.

et al. (2006) derived a total mass of the luminous components (i.e., not including the extended dark-matter halos) of galaxies using reasonable M/L ratios, it is reasonable to use $M_{\rm disk}$ rather than $M_{\rm gal}$ for the purpose of discussing the observed $M_{\rm nuc}$ versus $M_{\rm gal}$ relation. I will now briefly discuss the origin of this relation based on the results of the galaxy-scale simulations with SCs discussed in the previous section.

Figure 4 shows the time evolution of the mass ratio of the stellar nucleus to the stellar disk in a galaxy with $M_{\rm disk} = 10^9 {\rm M}_{\odot}$. Here, the nuclear mass is the total mass of SCs within the nuclear region (i.e., $R = 0.1R_{\rm disk}$) of the galaxy. It is not the total mass of the single stellar nucleus formed from multiple merging of SCs. The simulated nuclear mass ratio can rapidly become greater than 0.003 (in much less than 1 Gyr) because of orbital decay of massive SCs caused by DF of the clusters caused by the disk field stars. This result suggests that the formation of stellar galactic nuclei with masses similar to observed masses may be possible through SC mergers. However, the formation of stellar galactic nuclei through SC merging can proceed only in less luminous disk galaxies, because DF of SCs cannot be efficient for more luminous disk galaxies. Figure 4 shows that $M_{\rm nuc}/M_{\rm disk}$ can be as large as the observed value of 0.003, but *only for disk galaxies with* $M_{\rm disk} \leqslant 10^9$ ${\rm M}_{\odot}$. This result suggests that the observed $M_{\rm nuc}$ versus $M_{\rm disk}$ relation can be explained by SC mergers only for less luminous disk galaxies.

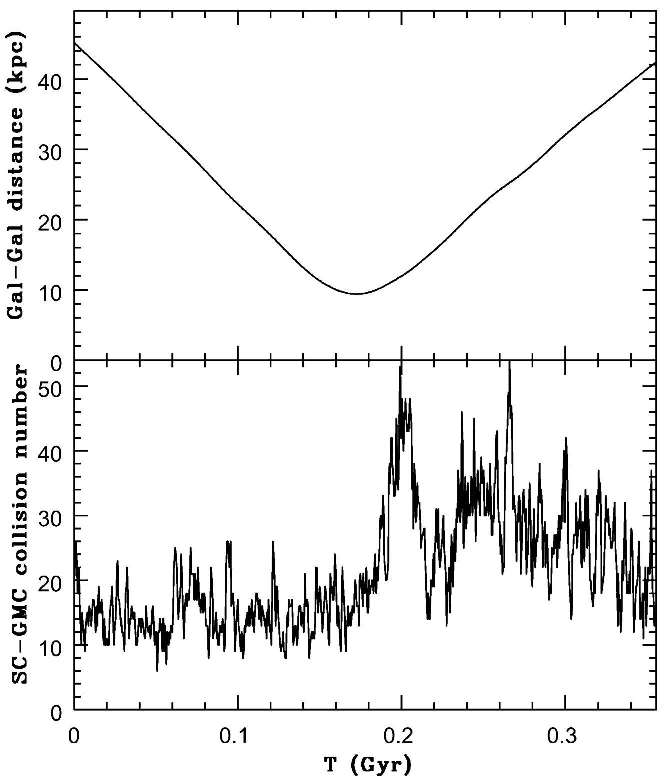

Figure 5. Time evolution of galaxy–galaxy distances *(top)* and SC–GMC collision number *(bottom)* for a galaxy-interaction model with a mass ratio of the two interacting galaxies of 2 and with a total mass of the primary galaxy of $4 \times 10^{10} {\rm M}_{\odot}$. If distances between SC–GMC pairs are less than 100 pc, they are regarded as colliding with each other. Initially, 100 SCs and 250 GMCs are distributed in the same way as the disk field stars, according to exponential radial distributions. Both SCs and GMCs have rotational kinematics similar to the disk field stars.

4. SC–GMC interaction in interacting galaxies

Strong dynamical interaction between SCs and GMCs and between different SCs is considered important for, e.g., the destruction of low-mass SCs (e.g., Gieles *et al.* 2006), the formation of rotationally flattened SCs through SC mergers (e.g., Makino *et al.* 1991) and the formation of binary SCs (e.g., Leon *et al.* 1999). It is, however, unclear how frequently such SC–GMC and SC–SC collisions/interactions can happen in galaxies owing to a lack of extensive galaxy-scale simulations that investigate directly and self-consistently such collisional events in galaxies. Thus, here I briefly discuss the SC–GMC and SC–SC collision rates in disk galaxies based on our galaxy-scale simulations with SCs and GMCs (Bekki *et al.*, in prep.). Since the parameter space for this numerical investigation is huge (i.e., regarding one's choice of different galaxy masses and structures), here I describe the results of the simulations for interacting disk galaxies with $M_{\rm disk} = 4 \times 10^9 M_\odot$ (corresponding to a total mass of $4 \times 10^{10} M_\odot$), which is reasonable for the LMC and Magellanic-type interacting galaxies. The canonical MFs for SCs and GMCs observed for the Galaxy and the LMC are adopted for the numerical models described below.

Figure 5 shows that galaxy interactions can significantly (up to a factor of ~ 3) increase the SC–GMC collision rate during the pericenter passage of the two galaxies if their mass ratio is as high as 2. About 94% of all SCs can strongly interact with GMCs within mutual SC–GMC distances of less than 100 pc during the tidal interaction. Although the mean relative velocity ($V_{\rm rel}$) of SC–GMC collisions for mutual distances of less than 100 pc is 68 km s^{-1}, only 19% of SCs that are strongly interacting with GMCs show $V_{\rm rel} < 20$ km s^{-1}. For the latter, SC–GMC merging of more massive SCs would be possible owing to $V_{\rm rel}$ being comparable to the internal velocity dispersion of the SCs. About 73% of all SCs can strongly interact with other SCs with mutual SC–SC distances of less than 50 pc during the tidal interaction and only 2% of SCs have $V_{\rm rel} < 20$ km s^{-1}. This implies that formation of SC–SC pairs during galaxy interaction may be very rare.

Figure 6 shows that the mass ratios of GMC to SC masses for strongly interacting SC–GMC pairs in galaxy interactions can be variable for the adopted MFs for SCs and GMCs.

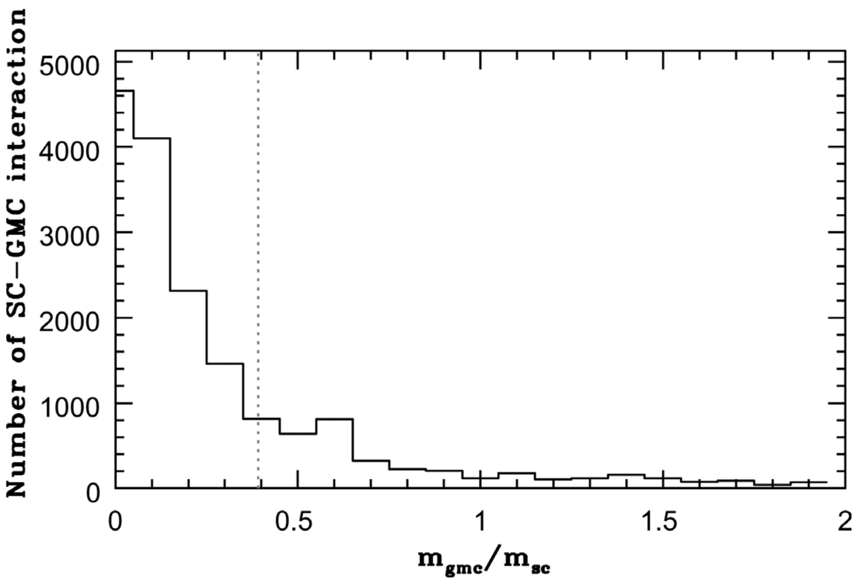

Figure 6. Distribution of the ratio of GMC to SC masses ($m_{\rm gmc}/m_{\rm sc}$) for colliding SC–GMC pairs in the same interaction model as shown in Figure 5. The mean value of $m_{\rm gmc}/m_{\rm sc}$ is indicated by the vertical dotted line, for comparison.

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Most of the SC–GMC pairs show smaller $m_{\rm gmc}/m_{\rm sc}$ (<1), with a mean of ~ 0.4. This suggests that some SCs, in particular those with smaller $m_{\rm gmc}/m_{\rm sc}$ ($0.3-0.5$), would accrete some gas during the SC–GMC interaction without being destroyed by GMCs owing to their smaller $m_{\rm gmc}/m_{\rm sc}$ (e.g., Bekki & Mackey 2009). If the gas transferred from GMCs to SCs during SC–GMC interactions can be used for further star formation in the SCs, the new stars can be identified as second-generation stars. There can be multiple stellar populations within individual SCs if the clusters experience strong SC–GMC interactions in interacting galaxies. One of the implications of these results is that the observed multiple stellar populations in intermediate-age GCs in the LMC (inferred from the double main-sequence turnoffs in their color–magnitude diagrams; e.g., Mackey *et al.* 2008) is due to SC–GMC collisions during the LMC–Galaxy interaction which occurred a few Gyr ago. Future, more sophisticated numerical simulations would need to be done to understand whether secondary star formation is really possible during SC–GMC collisions.

5. Tidal destruction of SCs in galaxy mergers

Although it is observationally clear that new SCs, some of which might eventually become GCs, are being formed in strongly interacting and merging galaxies like the Antennae system (Whitmore *et al.* 1995), formation and destruction processes of these new SCs during galaxy interactions/mergers are not so clear. Since SC 'infant morality' (i.e., disintegration of young SCs due largely to internal dynamical processes) in merging galaxies is extensively discussed in other contributions at this conference, here I focus

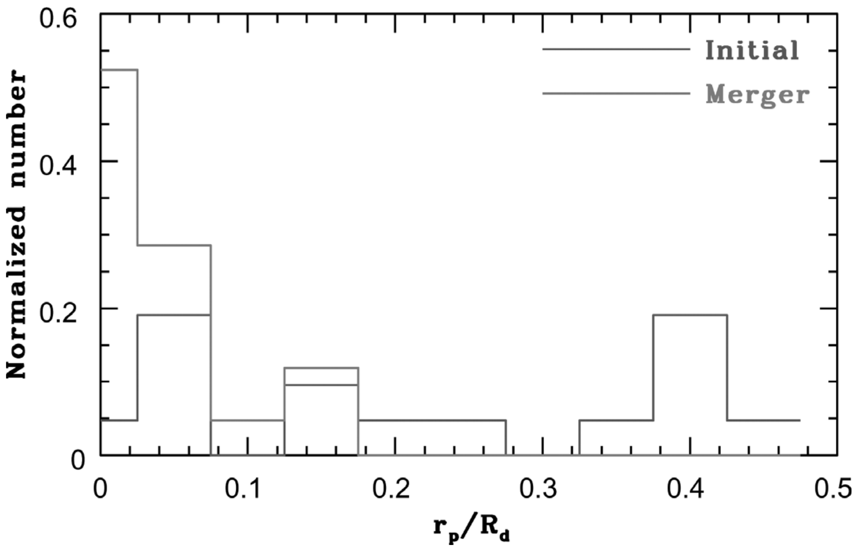

Figure 7. Normalized distribution of pericenter distances ($r_{\rm peri}$) in units of $R_{\rm disk}$ for orbits of 20 SCs from the initial disk (blue) and the galaxy merger (red) for a model with $M_{\rm disk} = 10^9 {\rm M}_{\odot}$. Here, $r_{\rm peri}$ for SCs in the initial disk are the initial distances of the SCs from the center of the galaxy, because initially SCs have almost circular orbits. Initially, these SCs are set to be within the merger progenitor disks. The nearly prograde–prograde merger of two disk galaxies with a pericenter distance of twice the disk size can eventually form a giant elliptical galaxy within 20 dynamical timescales. Note that most SCs in the merger show very small $r_{\rm peri}/R_{\rm disk}$ compared with those in the initial disk. This suggests that dynamics of major mergers can change circular orbits of the disk SCs into highly elongated orbits in the merger remnant.

on *destruction of initially bound SCs by strong tidal fields in galaxy mergers.* I base my discussion on the results of our numerical simulations (Bekki *et al.*, in prep.) of orbital evolution of SCs in mergers of two bulgeless disk galaxies with total masses of $M_{\rm disk} = 10^9 {\rm M}_\odot$ each.

Figure 7 shows the distribution of pericenter distances ($r_{\rm peri}$) in units of $R_{\rm disk}$ for the orbits of 20 SCs during a galaxy merger. It is clear that the SC orbits can become significantly elongated (i.e., the orbital eccentricity, $e_{\rm orb}$, becomes larger) during violent relaxation of galaxy mergers so that $r_{\rm p}$ can become rather small. For this model, the mean $r_{\rm p}$ and $e_{\rm orb}$ are $0.08R_{\rm disk}$ and 0.8, respectively. Consequently, SCs with highly radial orbits can pass through the inner region of the merger (remnant) to feel the much stronger tidal field there. This implies that a significant fraction of SCs in a galaxy mergers can either lose a large amount of their initial mass or be destroyed completely by the strong tidal field. These results do not depend strongly on model parameters such as the orbital configurations of galaxy mergers or the masses of the progenitor disk galaxies. These results also imply that, although new GCs can be formed during galaxy mergers (Whitmore *et al.* 1995; Bekki *et al.* 2002; Bournaud *et al.* 2008), their specific frequencies (S_N) do not increase significantly after galaxy mergers because of the tidal destruction of newly formed SCs. The origin of the observed high S_N in giant elliptical

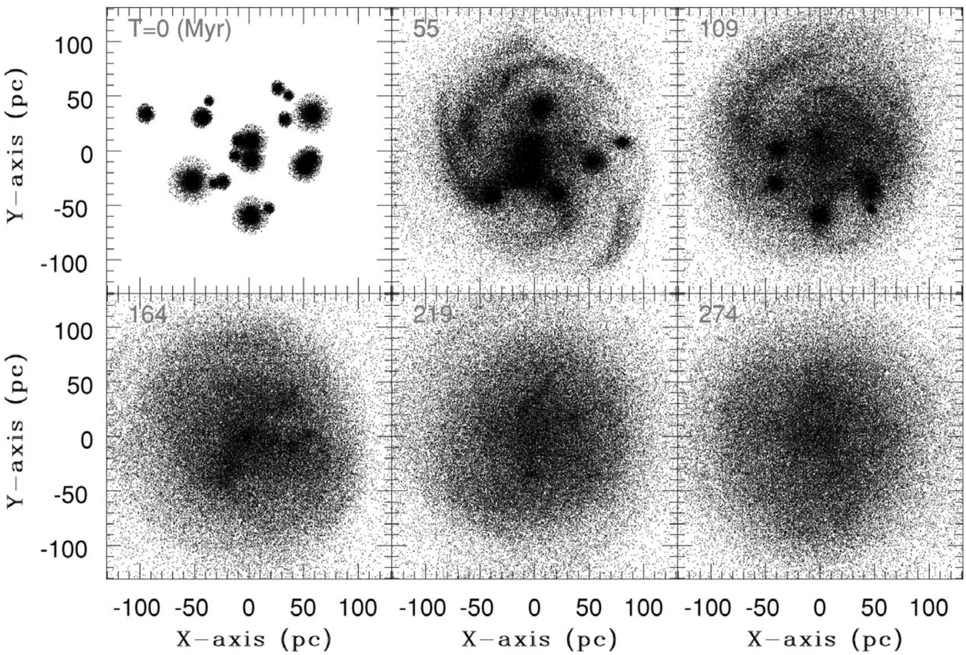

Figure 8. Time evolution of the distribution of SCs in a low-mass dark-matter halo projected onto the x–y plane. The 19 SCs are assumed to be unbound, in the sense that the total kinetic energy of a given SC ($T_{\rm kin}$) is four times greater than the absolute magnitude of the potential energy (W). This is done to mimic 50% mass loss of gas within newly formed SCs from GMCs due to energy feedback of massive OB stars and supernovae. The SC sizes and masses ($r_{\rm sc}$ and $m_{\rm sc}$, respectively) scale as $m_{\rm sc} \propto {r_{\rm sc}}^2$, which is similar to the scaling relation for GMCs. Owing to multiple-SC interactions and mergers and the strong tidal field of the dark-matter halo, most SCs eventually disintegrate to form a smooth distribution of field stars, which can be identified as a low-surface-brightness dwarf galaxy. If SCs are strongly bound initially (e.g., $2T_{\rm kin}/|W| = 1$; virial equilibrium), they cannot be destroyed as rapidly as in this model.

galaxies would not be so closely associated with the large number of new GCs formed during galaxy mergers that form giant elliptical galaxies.

6. Formation of low-mass dwarf galaxies from SCs

Given that the vast majority of field stars in galaxies originate from unbound or bound SCs (e.g., Lada & Lada 2003), it is reasonable to say that galaxies can be formed from SCs: they are fundamental building blocks of galaxies. If SCs are the first stellar objects formed in the very early phases of galaxy formation, one of the particularly interesting problems in terms of galaxy formation from multiple SCs relates to how the very first SCs, assumed to have formed in low-mass dark-matter halos, can disintegrate and then transform into a new galaxy dominated by field stars. Since this question has not been addressed by previous numerical simulations, here I discuss what can happen to multiple SCs in low-mass dark-matter halos when they interact and merge with one another and are influenced by the tidal fields of the halos. My analysis is based on our numerical simulations (Bekki *et al.*, in prep.).

Figure 8 shows that 19 initially unbound SCs with a total mass of $\sim 10^6 M_\odot$ in a dark-matter halo with a total mass of $\sim 10^9 M_\odot$ and with a Navarro, Frenk and White (NFW) profile can mutually interact with one another to form a diffuse dwarf galaxy in 274 Myr. The strong tidal field of the halo can play a vital role in this transformation from the initially clumpy distribution of SCs to the rather smooth field-star profile. As shown in Figure 9, the final galaxy has a very thick disk with a smaller ratio of maximum

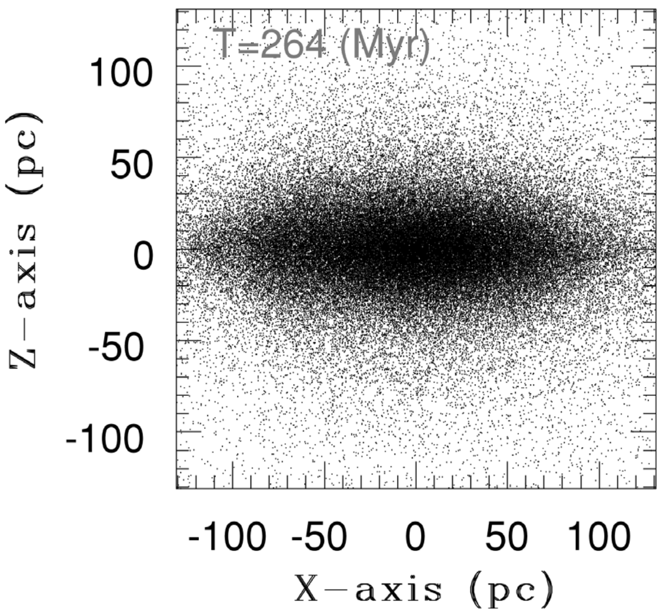

Figure 9. Final distribution of 19 SCs projected onto the x–z plane for the model shown in Figure 8. All unbound SCs completely disintegrate within 0.3 Gyr because of (i) the strong tidal field of their host dark-matter halo and (ii) mutual dynamical interactions between SCs. The field stars formed from disintegration of SCs can form a thick-disk component within the dark-matter halo. The initially unbound SCs can expand during their evolution because of rapid gas removal after their formation, and some fraction of the stars from the SCs can consequently form the stellar halo within the dark-matter halo. The formation of thick disks and stellar halos from disintegration of SCs within dark-matter halos is only possible in low-mass halos.

rotational velocity (V) to central velocity dispersion (σ) in the field stars ($V/\sigma \sim 3$). The thick-disk structure and kinematics are due largely to dynamical interactions between SCs and the dark-matter halo and between SCs and other SCs.

The final structural and kinematic properties of the simulated, very-low-mass dwarf galaxies depend strongly on the adopted initial MF of SCs and the total masses of the dark-matter halos. For example, the final disk-like structure of field stars in a dark-matter halo can be thicker in models with larger mean masses of SCs for a given initial mass of the halo. These results are based on rather idealized numerical models (e.g., fixed external tidal fields and a gravitational softening length for SC evolution), so that the internal dynamical evolution of individual SCs is not so self-consistently modeled. Thus, more self-consistent numerical simulations need to be done to gain a better understanding of how SCs form low-mass galaxies and how they evolve within them.

7. Conclusions

I have discussed five physical processes related to SCs, including (1) DF of SCs in disk galaxies, (2) multiple mergers of SCs in the central regions of galaxies, (3) collisions and mergers between SCs and GMCs and between different SCs, (4) tidal destruction of SCs in merging galaxies and (5) formation of low-mass dwarfs from multiple SCs in low-mass dark-matter halos. These processes are very important for a better understanding of the evolution of LFs and MFs of SCs and GCs, the origin of stellar galactic nuclei and their relationships with their host galaxies, formation of SCs with multiple stellar populations, evolution of S_N of GCs in early-type galaxies formed in major galaxy mergers and formation of very-low-mass galaxies at high redshifts. I have discussed these based mostly on galaxy-scale simulations in which internal evolution of SCs (e.g., two-body relaxation effects, binary formation and stellar evolution) is not properly modeled. Therefore, it is possible that future more sophisticated numerical simulations including *both galaxy- and cluster-scale internal dynamics* yield different results from those obtained in our simulations in terms of these five processes.

Ideally speaking, the internal dynamics of SCs in galaxies should be investigated using numerical codes by which we can investigate SC evolution in a *live (not a fixed) galactic potential*, represented by N-body particles. This is, first, because DF, which can not be investigated using models with fixed potentials, can significantly change the distances of SCs from their galactic centers (and thus the strengths of the galactic tidal fields, which are important for SC disintegration), and second because time-dependent global galactic structures (such as bars and spirals, which are hard to model as fixed, external gravitational forces) can dynamically influence SCs. Future sophisticated numerical simulations, including both cluster-scale (0.1–10 pc) internal and galaxy-scale (10 pc–10 kpc) global dynamics (e.g., Fujii *et al.* 2008) will allow us to investigate more self-consistently the formation and evolution of SCs within galaxies and thereby better understand not only the origin of the physical properties of SCs and SCSs, but also the formation of galaxies from their fundamental building blocks.

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