Dynamical friction of star clusters against disk field stars in galaxies: Implications on stellar nucleus formation and globular cluster luminosity functions

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ABSTRACT

We numerically investigate orbital evolution of star clusters (SCs) under the influence of dynamical friction by field stars of their host disk galaxies embedded in dark matter halos. We find that SCs with masses larger than $\sim 2 \times 10^5 M_\odot$ can show significant orbital decay within less than 1 Gyr due to dynamical friction by disk field stars in galaxies with disk masses ($M_d$) less than $10^9 M_\odot$. We also find that orbital decay of SCs due to dynamical friction is more remarkable in disk galaxies with smaller $M_d$ and higher mass-ratios of disks to dark matter halos. The half-number radii ($R_{h,sc}$) and mean masses within $R_{h,sc}$ of the SC systems (SCSs) in low-mass disk galaxies with $M_d \leq 10^9 M_\odot$ are found to evolve significantly with time owing to dynamical friction of SCs. More massive SCs that can spiral-in to the central regions of disks can form multiple SC systems with smaller velocity dispersions so that they can merge with one another to form single stellar nuclei with their masses comparable to $\sim 0.4\%$ of their host disk masses. Based on these results, we suggest that luminosity functions (LFs) for more massive globular clusters (GCs) with masses larger than $2 \times 10^5 M_\odot$ can steepen owing to transformation of the more massive GCs into single stellar nuclei through GC merging in less luminous galaxies. We also suggest that the half-number radii of GC systems can evolve owing to dynamical friction only for galaxies with their total masses smaller than $\sim 10^{10} M_\odot$.

Key words: globular clusters:general – galaxies:formation – galaxies:kinematics and dynamics – galaxies:halos – galaxies:star clusters

1 INTRODUCTION

Dynamical friction of SCs in galaxies have been discussed in many different contexts, such as formation of stellar galactic nuclei via merging of old GCs (e.g., Tremaine et al. 1975), transformation from non-nucleated dwarfs into nucleated ones (e.g., Oh & Lin 2000), physical meanings for the presence of the GC system (GCS) in the Fornax dwarf galaxy (e.g., Oh et al. 2001), and dark matter distributions of dwarf galaxies (e.g., Hernandez & Gilmore 1998; Goerdt et al. 2006; Inoue 2009). Orbital decay of GCs due to dynamical friction can significantly change spatial distribution of GCs and thus increase possibilities of them to be destroyed by strong galactic tidal fields (e.g., Vesperini 2000). Dynamical friction of SCs (including GCs) in galaxies is thus considered to be important for better understanding the evolution of GC luminosity functions (GCLFs) and that of half-number radii of the GCSs in galaxies (e.g., Vesperini 2000). Recently, van de Ven & Chang (2009) have suggested the importance of dynamical friction in the dynamical evolution of SCs around nuclear rings in galaxies.

Dynamical friction processes of SCs against disk field stars in disk galaxies are important for the following three reasons. Firstly, recent cosmological hydrodynamical simulations on the possible formation sites of first GCs (Kravtsov & Gnedin 2005) have shown that the present-day GCs can be formed within disk galaxies at high redshifts ($z \sim 3$). Secondly, less luminous disk galaxies like the Large Magellanic Cloud (LMC) have disk GC systems in which GCs have disky spatial distributions and rotational kinematics (e.g., Freeman et al. 1983; Olsen et al. 2004). Thirdly, previous theoretical studies suggested that the present-day dwarf ellipticals (dEs) were previously less luminous disk galaxies with no/little bulges (Mastropietro et al. 2004). Further-
more, previous observational results on physical properties of dwarf galaxies (e.g., Stiavelli et al. 2001) suggest similarity in nuclear density profiles of stars between dEs and spirals with exponential bulges; these appear to imply that understanding nucleus formation processes due to SC migration caused by dynamical friction in spirals can further lead to better understanding those in dwarfs. Although dynamical friction processes of SCs against disk field stars depend on physical properties of their host galaxies, such as disk masses, bulge-to-disk-ratios, and mass-ratios of disk to dark matter halo. Based on the present numerical results, we discuss the observed luminosity functions of GCs dependent on luminosities of their host galaxies (e.g., Jordán et al. 2006), formation processes of stellar galactic nuclei, and evolution of physical properties of GCs in galaxies.

The purpose of this paper is thus to investigate dynamical friction of SCs against disk field stars based on fully self-consistent numerical simulations on dynamical evolution of disk galaxies with SCs. We particularly investigate how dynamical friction of SCs against disk field stars depend on physical properties of their host galaxies, such as disk masses, bulge-to-disk-ratios, and mass-ratios of disk to dark matter halo. Based on the present numerical results, we discuss the observed luminosity functions of GCs dependent on luminosities of their host galaxies (e.g., Jordán et al. 2006), formation processes of stellar galactic nuclei, and evolution of physical properties of GCs in galaxies.

The plan of the paper is as follows: In the next section, we describe our numerical models for orbital evolution of SCs in disk galaxies. In §3, we present the numerical results mainly on (i) orbital evolution of SCs and (ii) the physical properties of SCs for variously different models. In §4, we discuss wide implications of the present results such as formation of stellar galactic nuclei by SC merging and evolution of mass and luminosity functions of SCs due to orbital decay of SCs caused by dynamical friction. We summarize our conclusions in §5.

### Table 1. The ranges of model parameters.

| Parameters | $M_{\text{gal}} \times 10^{10} M_\odot$ | $M_d \times 10^{9} M_\odot$ | $f_{d, c}$ | $f_{b, d}$ | Galaxy type | $M_{V, \text{low}}$ | $M_{V, \text{high}}$ |
|------------|-------------------------------------|--------------------------|-----------|-----------|-------------|-----------------|------------------|
| Value ranges | 0.1–10.0 | 0.1–10.0 | 0.01–0.1 | 0.0–1.0 | LSB or HSB | $-$6 (mag) | $-$12 $-$ $-$8 (mag) |

| a) The total mass of a galaxy. |
| b) The total mass of a disk. |
| c) The mass fraction of stellar disk ($= M_d / M_{\text{gal}}$) in a galaxy. |
| d) The mass fraction of a bulge ($= M_b / M_{\text{gal}}$) in a galaxy. |
| e) LSB and HSB represent low-surface brightness and high-surface brightness stellar disks, respectively. |
| f) The lower luminosity cut-off in the SC luminosity function. This parameter is fixed at $-6$ mag in all models (see the main text for main reasons for this). |
| g) The higher luminosity cut-off in the SC luminosity function. |

2 THE MODEL

We investigate orbital evolution of SCs in disk galaxies embedded in massive dark matter halos using the latest version of GRAPE (GRavity PipE, GRAPE-7) which is the special-purpose computer for gravitational dynamics (Sugimoto et al. 1990). All SCs are represented by point-mass particles rather than self-gravitating N-body systems so that we can not discuss internal stellar dynamics of SCs influenced by galactic potentials. Although evolution of SCs (e.g., internal stellar dynamics) from their formation within GMCs in a low-mass disk galaxy is discussed by our previous numerical simulations (e.g., Hurley & Bekki 2008), the present numerical code does not allow us to discuss this important issue: we plan to discuss this in our forthcoming papers.

Galaxies are represented by N-body particles so that SCs can feel gravitational influences of the live galactic potentials (e.g., dynamical friction). Non-axisymmetric structures such as bars and spiral arms in disk galaxies can change background stellar distribution and kinematics, which can be important for the effectiveness of dynamical friction that depends on density and velocities of background stars. Therefore, dynamical friction of SCs against disk field stars can be very complicated in the present study. Dynamical friction of disk SCs (i.e., SCs initially in stellar disks) against disk field stars is much more effective than that against dark matter halos in the present study. Therefore, the orbital decay of disk SCs demonstrated in the present study is due mainly to gravitational interaction between disk field stars and SCs.

2.1 Disk galaxy model

Since our numerical methods for modeling dynamical evolution of late-type disk galaxies have already been described by Bekki & Peng (2006), we give only a brief review here. The total disk mass and the size of a disk of a disk galaxy with the total mass of $M_{\text{gal}}$ are $M_d$ and $R_d$, respectively. Time is measured in units of $t_g = (R_d^3 / G M_{\text{gal}})^{1/2}$, where $G$ is the gravitational constant and assumed to be 1.0. If we adopt $M_{\text{gal}} = 1.0 \times 10^{10} M_\odot$ and $R_d = 2.3$ kpc as a fiducial value, then $t_g = 1.6 \times 10^7$ yr. The model with this fiducial value is referred to as “the standard model”. The disk is composed of a dark matter halo, a stellar disk, and a stellar bulge. We mainly investigate late-type, bulge-less galaxies, because we mainly discuss SC evolution in low-mass galaxies.

The mass ratio of the dark matter halo (with the mass of $M_{\text{dm}}$) to the stellar disk in a disk model is a free parameter ranging from 9 to 49.0 in order to investigate galaxies with different $M_{\text{gal}}$ thus different mass-to-light-ratio. We adopt the density distribution of the NFW halo (Navarro, Frenk & White 1996) suggested from CDM simulations:

$$\rho(r) = \frac{\rho_0}{(r/r_s)(1 + r/r_s)^2},$$

(1)

where $r$, $\rho_0$, and $r_s$ are the spherical radius, the characteristic density of a dark halo, and the scale length of the halo, respectively. The $c$ parameter ($= r_s / r_{\text{vir}}$), where $r_{\text{vir}}$ is the virial radius of the NFW profile) for a galaxy with $M_{\text{dm}}$ is chosen according to the predicted $c$-$M_{\text{dm}}$ relation in the LCDM simulations (e.g., Neto et al. 2007). For example,
reasonable $c$ values for disk galaxies with $M_{\text{gal}} = 10^{10} M_\odot$ are 12.9 (also $v_{\text{rot}}$ is $\sim 10 R_d$). The stellar bulge with a mass $M_b$ and radius $R_b$ is represented by the Hernquist profile with the scale-length of $0.2 R_b$. The bulge mass fraction ($M_b/M_d$) is referred to as $f_b$.

The radial ($R$) and vertical ($Z$) density profiles of the disk are assumed to be proportional to $\exp(-R/R_0)$ with scale length $R_0 = 0.2$ and to $\text{sech}^2(Z/Z_0)$ with scale length $Z_0 = 0.04$ in our units, respectively; the stellar disk follows this exponential distribution. In addition to the rotational velocity caused by the gravitational field of disk, bulge, and dark halo components, the initial radial and azimuthal velocity dispersions are assigned to the disc component according to the epicyclic theory with Toomre’s parameter $Q = 1.5$. The vertical velocity dispersion at given radius is set to be 0.5 times as large as the radial velocity dispersion at that point, as is consistent with the observed trend of the Milky Way (e.g., Wielen 1977).

We investigate models with different $M_{\text{gal}}$ and adopt the Freeman’s law (Freeman 1970) to determine $R_0$ of a disk galaxy according to its disk mass:

$$R_0 = 3.5 \left( \frac{M_d}{6 \times 10^{9} M_\odot} \right)^{0.5} \text{kpc.}$$

Structural and kinematical properties of dark matter halos and stellar disks are assumed to be self-similar between models with different $M_{\text{gal}}$. We also investigate low-surface brightness (LSB) models with different $M_{\text{gal}}$ in which $R_0$ of a disk galaxy is determined as:

$$R_0 = 8.8 \left( \frac{M_d}{6 \times 10^{9} M_\odot} \right)^{0.5} \text{kpc.}$$

Both the total particle number of dark matter halo ($N_h$) and that of the stellar disk ($N_d$) in a bulgeless disk model are 500000. The total number for bulge ($N_b$) in a model depends on $M_b$ such that $N_b = N_d M_b/M_d$. The fixed gravitational softening length is 0.008$R_d$, which corresponds to 19pc in the standard model with $M_d = 10^{9} M_\odot$. The mass-ratio of the lowest-mass SC to each disk field star is more than 10 owing to the adopted particle number ($\sim 10^6$) so that we can properly investigate dynamical friction processes of SCs by disk field stars. The leapfrog integration scheme with a fixed time step of 0.02$t_g$ is adopted for all models.

### 2.2 SC model

Since we focus on orbital evolution of long-lived SCs in disk galaxies, we adopt the canonical luminosity function (LF) observed for old GCs (Harris 1991):

$$\Phi(M) = C \times e^{-\left(M - M_0\right)^2/2 \sigma_m^2},$$

where $C$ is a constant, $M$ is the magnitude of a SC, $M_0 = -7.27$ mag in the $V$ band (Harris 1991), and $\sigma_m = 1.2$ mag. We assume that $M_0$ and $\sigma_m$ should be the same between different models in order to show more clearly how dynamical friction processes of SCs depend on physical properties of their host galaxies. The mass function (MF) of SCs (SCMFs) is derived from the LF of SCs (SCLFs) for a reasonable stellar-mass-to-light-ratio.

The $V$-band magnitudes of SCs for lower and higher cut-off luminosities/masses in SCLFs/SCMFs are described as $M_{V,\text{low}}$ and $M_{V,\text{high}}$, respectively. $M_{V,\text{low}}$ and $M_{V,\text{high}}$ are set to be $-6$ mag and $-10$ mag, respectively for most models. Although we consider these values to be reasonable and realistic, we investigate models with different $M_{V,\text{high}}$ for comparison. If we adopt $M_{V,\text{low}}$ significantly larger than $-6$ mag, the mass of a SC can be comparable to each disk field star in some models so that we can not properly investigate dynamical friction processes. We therefore consider that it is the best for the present study to fix $M_{V,\text{low}}$ at a reasonable value. The stellar-to-mass-to-light-ratio is 3.2 for SCs in all models to allocate a mass ($m_{\text{SC}}$) to each SC particle.

The total number of SCs in a galaxy is determined by $S_N$ of the galaxy, where $S_N$ is the specific frequency of the SC
system. The specific frequency is defined as follows (Harris & van den Bergh 1981):

\[ S_N = N_{\text{sc}} \times 10^{0.4(M_V + 15)}, \]

where \( N_{\text{sc}} \) and \( M_v \) are the total number of SCs in a galaxy and V-band absolute magnitude of the galaxy, respectively. Thus, \( N_{\text{sc}} \) is determined by \( S_N \) and \( M_v \) with a reasonable assumption on the mass-to-light-ratio for stars (for converting \( M_v \) into \( M_L \) in galaxies).

The observed dependence of \( S_N \) on \( M_V \) has “U-shape” in the sense that the galaxy luminosity dependence of \( S_N \) is different between galaxies below and above a threshold luminosity, \( M_{V,\text{th}} \), which is around \( -19.5 \text{ mag} \) (Bekki et al. 2006). We here use the following form for the \( S_N-M_V \) relation (Bekki et al. 2006):

\[ S_N(x) = A_1 \times 10^{K_{1x}} + (S_{N,\text{th}} - A_1) \times 10^{K_{2x}}, \]

where \( x = \frac{M_V - M_{V,\text{th}}}{M_{V,\text{th}}} \) and \( S_{N,\text{th}} \) is \( S_N \) at \( M_V = M_{V,\text{th}} \). Parameter values of \( A_1, K_1, K_2, M_{V,\text{th}}, \) and \( S_{N,\text{th}} \) can be determined by fitting to observations. A reasonable model fit to observational data sets have \( M_{V,\text{th}} = -19.5 \text{ mag} \), \( S_{N,\text{th}} = 1.0, A_1 = 0.5, K_1 = -6, \) and \( K_2 = 4 \) (see Fig. 1 in Bekki et al. 2006).

We mainly investigate the “standard” SC model in which \( M_d = 10^9 M_\odot \), \( M_d/L = 4.0 \) (where \( L \) is the total luminosity of the disk), \( S_N = 6.8 \) (thus \( N_{\text{sc}} = 20 \)). This model can be consistent with the observed U-shaped \( S_N-M_V \) relation. The models with the same \( S_N-M_V \) relation as that adopted in the standard model have \( N_{\text{sc}} = 3 \) for \( M_d = 10^8 M_\odot \) and \( N_{\text{sc}} = 117 \) for \( M_d = 10^9 M_\odot \) in the present study. We however investigate models with \( N_{\text{sc}} \) smaller/larger than those consistent with the adopted \( S_N-M_V \) relation for comparison.

We assume that the initial distribution and kinematics of the SCS in a disk galaxy are exactly the same as those of the disk components (i.e., rotating, exponential disk). This is a reasonable assumption, given that the vast majority of stars are formed as bound and unbound SCs in the Galactic disk (e.g., Lada & Lada 2003). For the adopted exponential distribution of a SCS, we allocate each SC particle 3D-velocities as follows. We first search for the nearest disk particle (i.e., disk field star) for each SC particle and then allocate the 3D velocities of the disk particle to the SC one. Thus the initial SCS in a galaxy has a thin disk configuration and rotational kinematics.

In order to discuss the effectiveness of dynamical friction of disk SCs against disk field stars, we also briefly investigate orbital evolution of halo SCs that are initially in halo regions of galaxies. The number of halo SCs is the same as that of disk SCs in a galaxy and its spatial distribution is described as a power-law with the power-law index of \(-3.5 \) as observed for the Galactic GCs (e.g., van der Bergh 2000). The initial half-number radius of the halo SCs in a galaxy is \( 1.4 R_0 \) as observed for the Galactic GCs (i.e., the half-number radius of 5 kpc for the GCS and \( R_0 = 3.5 \text{ kpc} \) for the stellar disk; van der Bergh 2000). Kinematical properties of the halo SCs are assumed to be the same as those of the dark matter halos of their host galaxies (i.e., isotropic velocity dispersions determined by mass distributions of the galaxies).

2.3 Parameter study

We mainly investigate dynamical friction processes of SCs with different initial masses, their orbital evolution and the final distribution of SCs in the standard model with \( M_d = 10^9 M_\odot, f_0 = 0, f_d = 0.1, N_{\text{sc}} = 20, \) and \( M_{V,\text{high}} = -10 \text{ mag} \). We also investigate 40 models with different \( M_d, f_0, f_d, N_{\text{sc}}, M_{V,\text{high}}, \) central densities of stellar disk (i.e., whether disks are LSB or HSB, where LSB and HSB represent low-surface brightness and high-surface brightness disk galaxies, respectively) and structures of dark matter halos in order to better understand the effectiveness of dynamical friction in disk galaxies with different physical properties. The range of model parameters investigated are shown in the Table 1.

In order to discuss formation of stellar nuclei in disk galaxies, we investigate time evolution of the total mass of SCs within \( 0.1 R_d \) for each model. We consider that SCs transferred to the central \( 0.1 R_d \) owing to dynamical friction can quickly merge with one another to form a single massive SC that can be identified either as a nuclear SC or a stellar galactic nucleus. Since SCs are represented by point-mass particles in the present simulations, nucleus formation via SC merging can not be investigated in a fully self-consistent manner. Previous and recent numerical simulations in which SCs are represented by N-body particles have confirmed that nuclear SCs can merge to form a single nucleus in a galaxy (e.g., Capuzzo-Dolcetta & Micocchi 2008). We thus consider that it is appropriate for the present study to briefly discuss formation of stellar galactic nuclei via SC merging in central regions of galaxies based on our simulations.

Thus the total mass of the stellar nucleus in a disk galaxy at each time step in each simulation (\( M_{\text{nuc}} \)) is de-
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2.4 Comparison with analytical works

Previous analytical works showed that dynamical friction processes of SCs within galaxies depend on masses of SCs and physical properties of their host galaxies (e.g. Binney & Tremaine 1987). These analytical works would be quite useful and helpful in better understanding numerical results, though they did not investigate dynamical friction of SCs against disk field stars. The time-scale of dynamical friction ($t_{\text{fric}}$) for typical GCs with masses ($M_{\text{gc}}$) of $2 \times 10^5 M_\odot$ within galactic halos of luminous galaxies is considered to be quite long (e.g., Binney & Tremaine 1987). For the Galaxy with the circular velocity $v_c = 220$ km s$^{-1}$ and the Coulomb logarithm $\ln \Lambda = 10$, $t_{\text{fric}}$ can be estimated as follows:

$$ t_{\text{fric}} = 1.2 \times 10^{11} \left( \frac{r_i}{2 \text{kpc}} \right)^2 \left( \frac{v_c}{220 \text{km s}^{-1}} \right) \left( \frac{M_{\text{gc}}}{2 \times 10^5 M_\odot} \right)^{-1} \text{yr}, \quad (8) $$

where $r_i$ is the distance of a GC from the center of its host galaxy. For a galaxy with $v_c = 70$ km s$^{-1}$ and $\ln \Lambda = 10$,

$$ t_{\text{fric}} = 1.8 \times 10^9 \left( \frac{r_i}{1 \text{kpc}} \right)^2 \left( \frac{v_c}{70 \text{km s}^{-1}} \right) \left( \frac{M_{\text{gc}}}{10^5 M_\odot} \right)^{-1} \text{yr}. \quad (9) $$

Therefore, although dynamical friction can not be important for evolution of normal SCs and GCs within luminous galaxies like the Galaxy, it can significantly change physical properties of SCs and those of SCSs in dwarf galaxies. The above results also show that dynamical friction of SCs can be more effective for SCs initially located in the inner regions of galaxies.

These estimation is for dynamical friction of SCs against galactic halos so that we can not rely on these for understanding the present numerical results for those against disk field stars. However, the above analytical estimation would be still useful for (i) understanding the differences in $t_{\text{fric}}$ between dynamical friction against galactic halos and that against disk field stars and (ii) discussing dependences of the present results on $M_d$ (thus on $v_c$) in a qualitative manner.
Table 2. A brief summary of the results for the five representative models with different disk masses.

| $M_d$ ($\times 10^9 M_\odot$) | $M_{\text{nuc}}$ ($\times 10^6 M_\odot$) | $M_{\text{nuc}}/M_d$ | $\bar{R}_f/R_i$ | comments |
|-----------------------------|----------------------------------------|----------------------|-----------------|----------|
| 0.1                         | 0.5                                    | 0.0049               | 0.28            | low-mass disk model |
| 0.5                         | 2.2                                    | 0.0043               | 0.50            | standard model |
| 1.0                         | 4.3                                    | 0.0043               | 0.55            | standard model |
| 5.0                         | 3.0                                    | 0.0006               | 0.67            | high-mass disk model |
| 10.0                        | 2.8                                    | 0.00028              | 0.83            | high-mass disk model |

$^a$ The total mass of a disk. For these five disk models, other model parameters such as $f_d$ and $f_b$ are exactly the same between the five.

$^b$ The total mass of the stellar nucleus in a disk: This is the total mass of SCs within $0.1 R_d$.

$^c$ The nuclear mass fraction of a disk.

$^d$ The mean value of $R_f/R_i$, where $R_i$ and $R_f$ are initial and final radii of SCs from the center of their host galaxy. This mean value is estimated for SCs with $R_f/R_i \leq 1$ so that we can more appropriately measure the degree of orbital decay of SCs due to dynamical friction.

Figure 6. Time evolution of the mass-ratio of the nucleus to the disk ($M_{\text{nuc}}/M_d$) in the standard model. The dotted line is the observed mean of $M_{\text{nuc}}/M_d$. See the main text for the details of the method to estimate $M_{\text{nuc}}$.

Figure 7. The ratios of final $R$ ($R_f$) to initial one ($R_i$) as a function of $R_i$ for SCs in four models with $M_d = 10^8 M_\odot$ (upper left), $M_d = 5 \times 10^8 M_\odot$ (upper right), $M_d = 5 \times 10^9 M_\odot$ (lower left), and $M_d = 10^{10} M_\odot$ (lower right).

Figure 8. The same as Fig. 7, but for four models with $M_{\text{dm}}/M_d = 19$ (upper left), $M_{\text{dm}}/M_d = 49$ (upper right), $M_{\text{b}}/M_d = 0.17$ (lower left), and $M_{\text{b}}/M_d = 1$ (lower right).

distribution of SCs can change with time not only because of the dynamical evolution of the disk but also because of dynamical friction of SCs against the disk field stars. The half-number radius of the SCS evolves from $0.38 R_d$ (corresponding to $= 0.86$ kpc) to $0.30 R_d$ ($= 0.68$ kpc), which reflects that dynamical friction of SCs can cause orbital decay of massive SCs within the disk. The total number of SCs within $0.1 R_d$ in the disk can gradually increase so that a multiple SC system with the total mass ($m_{\text{sc}}$) of $4.3 \times 10^6 M_\odot$ can form in the nuclear region of the disk. The $x-$, $y-$, and $z-$components of velocity dispersions of the multiple SCs are 17.7 km s$^{-1}$, 23.6 km s$^{-1}$, and 3.2 km s$^{-1}$. The velocity dispersions comparable to internal velocity dispersions of their nuclear massive SCs suggest that the nuclear SCs can soon merge to form a single nucleus.

Figs. 2 and 3 show orbital evolution projected onto the $x$-$y$ and $x$-$z$ planes for SCs with two different masses. In both case, the distances from the center of the stellar disk ($R$) become significantly smaller owing to orbital decay caused by dynamical friction against disk field stars. The extent to which a SC can decay its orbit owing to dynamical friction
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3.2 Parameter dependences

Dynamical friction processes of SCs in disk galaxies depend strongly on model parameters such as \( M_d, M_{\text{dis}}/M_d \) (= \( 1/f_3 - 1 \)), \( M_s/M_d \) (= \( f_5 \)), central stellar densities of disks, and \( M_{V, \text{high}} \). The derived \( M_d \)-dependence is the most important result in the present study so that it is briefly summarized in the Table 2. We illustrate the derived dependences on model parameters as follows:

(i) Orbital decay of SCs due to dynamical friction is more important in less massive host galaxies, mainly because relative velocities \( (v_{\text{rel}}) \) between SCs and disk field stars (which are comparable to stellar velocity dispersions of the disks) are smaller in the galaxies: the frictional drag force can be proportional to \( v_{\text{rel}} \) (see 7.18 in Binney & Tremaine 1987). Fig. 7 shows that \( R_i/R_f \) is systematically smaller in disk galaxies with smaller \( M_d \) for a fixed \( f_3 \). Fig. 7 also shows that for disks with \( M_d \geq 5 \times 10^8 M_\odot \), no/few SCs can show significant orbital decay \( (R_i/R_f < 0.4) \), which means that dynamical friction of SCs is not so important in their orbital evolution.

(ii) Dynamical friction of SCs by disk field stars is less effective in galaxies with smaller \( f_3 \), mainly because stellar densities of disk field stars are lower so that frictional drag force can be weaker. Fig. 8 shows that for disks with \( M_d/M_\odot = 49 \), only a few SCs can show significant orbital decay \( (R_i/R_f < 0.4) \), which implies that dynamical friction of SCs cannot be so important in orbital evolution of SCs in the early phase of disk evolution of galaxies when the mass fractions of disk stars can be very small. Fig. 8 also shows that a smaller fraction of SCs have \( R_i/R_f > 1 \), which reflects that radial redistribution of SCs due to the presence of non-axisymmetric structures (spirals and bars) does not happen in galaxies with smaller degrees of self-gravitating.

(iii) Galactic bulges appear to be less important in orbital decay of SCs within disks in comparison with other galactic properties such as \( M_\odot \) and \( f_3 \). Fig. 8 shows no remarkable differences between models with different \( f_3 \) \((=0.17 \text{ and } 1.0)\), though \( f_3 \) can be an important parameter which determines whether stellar bars can form and thus affect orbital evolution of SCs.

(iv) The time scale of dynamical friction of SCs by disk field stars is longer in LSBs than in HSBs, because stellar densities of background field stars can be key factors for the effectiveness of dynamical friction. As a result of this, formation of stellar nuclei via SC merging can proceed more slowly in LSBs. For example, \( M_{\text{nuc}} \) can become \( \sim 10^5 M_\odot \) only after 2.4Gyr orbital evolution of SCs in the LSB model in which \( R_d \) is by a factor of 2.5 larger than that in the standard model (and other model parameters are the same as those in the standard model).

(v) Final properties of SCs (e.g., \( M_{\text{nuc}} \), and the formation processes of nuclear diffuse SCs (thus nucleus formation processes) in galaxies depend on initial MFs (e.g., \( M_{V, \text{high}} \)). For example, \( R_{\text{b,sc}} \) can evolve more rapidly and have smaller final values in models with smaller \( M_{V, \text{high}} \) (i.e., larger \( m_{\text{sc}} \) for the most massive SCs) in the present study (e.g., \( R_{\text{b,sc}} = 0.2R_d \) for models with \( M_{V, \text{high}} = -11 \text{ mag} \)). Also final \( M_{\text{nuc}} \) is larger in models with smaller \( M_{\text{min}} \) (e.g., \( M_{\text{nuc}}/M_d = 0.02 \) for \( M_{V, \text{high}} = -11 \text{ mag} \)). This result implies that formation processes of stellar galactic nuclei (e.g., whether dwarfs are nucleated or non-nucleated) depend on original MFs of SCs in galaxies.

4 DISCUSSION

4.1 Evolution of SC luminosity functions

The present study has first shown that more massive SCs can spiral-in to the nuclear regions of galactic disks owing to dynamical friction within less than \( \sim 1 \) Gyr in low-mass disk galaxies. It is highly likely that these multiple SCs in nuclear regions of disk galaxies can merge with one another to form stellar galactic nuclei (or single massive nuclear SCs). If this is the case, then the merged SCs (i.e., stellar galactic nuclei or nuclear SCs) would not be identified as ordinary SCs in observations. Therefore, it is meaningful for the present
study to investigate SCMFs located within \( R \geq 0.1R_d \) for comparing the simulated SCMFs with the observed ones. In the followings, we assume that MFs are for SCs located within \( R \geq 0.1R_d \) (i.e., excluding the nuclear SCs in the simulations).

Fig. 9 shows that no SCs with \( \log_{10}(m_{sc}/M_\odot) > 5.9 \) can be seen in the final MF for the standard model, because more massive SCs spiral-in to nuclear regions of disk galaxies more rapidly owing to dynamical friction of SCs against disk field stars. This result implies that MFs of SCs for \( 5.0 < \log_{10}(m_{sc}/M_\odot) \) (i.e., higher-mass end) can steepen significantly in comparison of their original MFs (at the epoch of SC formation) owing to dynamical friction of SCs. Furthermore, given that dynamical friction of SCs against disk field stars is more effective in less massive disk galaxies, the MFs can more significantly steepen in less massive disk galaxies. Thus, it is highly likely that the SCMFs can be steeper in less massive disk galaxies.

Based on observational studies of GCLFs for the early-type galaxies in the ACS Virgo Cluster Survey, Jordán et al. (2006) showed that the GCMFs for relatively high masses (\( m_{sc} \geq 3 \times 10^5M_\odot \)) are steeper in less luminous galaxies in the Virgo cluster. They suggested that since GCMFs are not strongly affected by dynamical evolution of GCs (e.g., dynamical friction) over a Hubble time, the steeper GCMFs arise from variations in initial conditions. Our results however imply that dynamical friction of SCs against disk field stars is so effective as to change the shapes of GCMFs within a relatively short time scale. Our results also imply that if these less luminous early-type galaxies were formed from disk galaxies either by galaxy interactions or by major mergers, their GCMFs can be steeper owing to changes of GCMFs in their progenitor disks caused by dynamical friction.

### 4.2 Formation of stellar galactic nuclei

Since Tremaine et al. (1975) first investigated dynamical evolution of GCs interacting with background stars through dynamical friction in M31 to discuss nucleus formation in M31, many authors discussed formation of stellar galactic nuclei via 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 merging of SCs in the inner regions of galaxies lead to the formation of stellar galactic nuclei with their projected radial density profiles similar to the observed ones (e.g., Capuzzo-Dolcetta & Miocchi 2008). Although these works did not discuss potential importance of dissipative gas dynamics and star formation in the formation of stellar galactic nuclei (e.g., Bekki et al. 2006; Bekki 2007), they significantly advanced our understanding dynamical evolution of multiple SC systems in galaxies.

One of remaining questions in the SC merger scenario of nucleus formation is whether the scenario can explain the observed relation between stellar nucleus masses and their host galaxy ones. Since the observational study by Côté et al. (2006) derived total mass of the luminous components...
ponents (i.e., not those for entire galaxies including the extended dark matter halos) of galaxies by using reasonable $M/L$, it is reasonable to use $M_d$ rather than $M_{gal}$ for the purpose of discussing the observed $M_{nuc} = 0.003M_d$ relation. Fig. 10 shows $M_{nuc}/M_d$ as a function of $M_d$ for the five models in which only $M_d$ are different between them. The simulated $M_{nuc}/M_d$ is close to the observed value of 0.003 for less luminous disk galaxies with $M_d \leq 10^9 M_\odot$. SCs can lose a significant fraction of their original masses during their orbital evolution in galaxies (e.g., Fujii et al. 2008), which is not considered at all in estimating $M_{nuc}/M_d$ in the present study. Thus the simulated $M_{nuc}/M_d$ for less luminous disks can be regarded as fairly consistent with observations.

Fig. 10 also shows that formation of stellar galactic nuclei with $M_{nuc}/M_d \sim 0.003$ by SC merging is not possible in more luminous disks owing to ineffective dynamical friction. Therefore, the result implies that if the observed $M_{nuc} = 0.003M_d$ relation can be hold for all galaxies, the SC merger scenario may well have a serious problem in explaining the observation. However, galaxies are more likely to have massive black holes (MBHs) rather than stellar nuclei in more luminous galaxies with $M_d \geq 10^{10} M_\odot$ (e.g., Ferrarese et al. 2006), though it is not so clear whether these galaxies with MBHs also have stellar nuclei (i.e., MBHs and stellar nuclei coexist in galaxies). Thus it would be currently reasonable to claim that the SC merger scenario is a promising one for the formation of stellar galactic nuclei in galaxies.

4.3 Compassion with dynamical friction by galactic halos

We have first shown that dynamical friction of SCs against disk field stars can be so effective in low-mass disk galaxies so that orbital decay of SCs can be as significant as to change physical properties (e.g., half-number radii and SCMFs) of their SCSs. Previous theoretical and numerical works focused exclusively on dynamical friction of halo SCs (e.g., old GCs) against dark matter halos and showed that the time scale of orbital decay of SCs due to dynamical friction against dark matter halos is relatively long (a few to several Gyr) even for low-mass dwarfs like the Fornax (e.g., Goerdt et al. 2006 for the cuspy NFW profile of its dark matter halo). Since they did not investigate the influences of stellar disks on orbital evolution of halo SCs through dynamical friction, it is worthwhile for the present study to investigate how halo SCs evolve in disk galaxies if they can experience dynamical friction against both dark matter halos and against disk field stars.

Fig. 11 shows that orbital decay of halo SCs due to dynamical friction against halos and disks is much less significant owing to (i) lower mass densities of the halos and (ii) larger velocity differences in the SCs and dark matter halos for the standard model. The mean $R_t/R_h$ for the halo SCs is 1.53, which is by a factor of 2 larger than that for the disk SCs. Only some more massive SCs with $m_{sc} \geq 2 \times 10^8 M_\odot$ can show significant orbital decay (i.e., decreasing apocenter distances of their orbits) for halo SCs. This less effective dynamical friction in halo SCs is a common feature in the present models, which suggests that the presence of disks in galaxies does not significantly change dynamical friction processes of halo SCs. It should be however stressed that the halo SCs initially in the inner region of the disk galaxy in the standard model shows a slightly flattened final spatial distribution: this can be due to relatively strong dynamical friction between halo SCs and disk field stars in the inner regions of galaxies.

5 CONCLUSIONS

We have investigated orbital evolution of SCs being influenced by dynamical friction of disk field stars based on galaxy-scale numerical simulations on dynamical evolution of disk galaxies. We have investigated models with various different model parameters in order to understand dependences of the effectiveness of dynamical friction of SCs on physical properties of disk galaxies. We summarize our principle results as follows.

(1) Dynamical friction of SCs against disk field stars is much more effective in orbital decay of SCs in comparison with that against galactic halos in disk galaxies. For example, the half-number radius of the SCS ($R_{h,sc}$) in a galaxy with $M_d = 10^9 M_\odot$ can decrease by $\sim 30\%$ owing to orbital decay of SCs caused by dynamical friction within well less than 10$^9$ yr for a reasonable MF of SCs. However orbital decay of SCs due to dynamical friction can be more clearly seen only for more massive SCs (e.g., those with $m_{sc} \geq 2 \times 10^9 M_\odot$).

(2) Dynamical friction processes of SCs against disk field stars depend on physical properties of their host galaxies. For example, the dynamical friction is much more effective in disks with lower $M_d$ owing to smaller stellar velocity dispersions. As a result of this, $R_{h,sc}$ can more rapidly evolve with time in disks with lower $M_d$. Evolution of SCSs in more massive disks (with $M_d \sim 10^{10} M_\odot$) cannot be clearly seen in the present study, which implies dynamical friction is important only for evolution of SCSs (e.g., $R_{h,sc}$) in less massive disk galaxies.

(3) Dynamical friction of SCs by disk field stars is more effective in disks with higher degrees of self-gravitating of the disks (e.g., higher $f_d$), which implies that higher stellar densities and non-axisymmetric structures such as bars and spiral arms can promote dynamical friction. Orbital decay of SCs due to dynamical friction in disks does not depend so strongly on bulge masses of the disks for $0 \leq f_b \leq 1$ in the present study. Evolution of SCSs due to orbital decay of SCs caused by dynamical friction is more important in HSBs than in LSBs.

(4) More massive SCs can spiral-in to the nuclear regions ($R < 0.1 R_d$) of disk galaxies owing to dynamical friction so that they can form multiple SC systems there in less massive disk galaxies with $M_d \leq 10^9 M_\odot$. These systems show velocity dispersions comparable to or less than internal stellar velocity dispersions of SCs so that they are likely to merge quickly with one another to form single massive SCs there. Thus formation of stellar galactic nuclei via merging of more massive SCs is possible in less massive disk galaxies.

(5) The observed $M_{nuc} - M_d$ relation (i.e., $M_{nuc} \sim 0.003 M_d$) for less luminous galaxies can be closely associated with formation of stellar galactic nuclei by SC merging. The LF/MFs for more massive SCs in SCSs of disk galaxies can steepen owing to the formation of stellar galac-
tic nuclei through merging of more massive SCs inwardly transferred to the nuclear region of galaxies. This steeping of SCLF/MFs due to dynamical friction can be more significant in less massive galaxies.

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APPENDIX A: ORBITAL EVOLUTION OF INDIVIDUAL SCs

Fig. A1 shows time evolution of $R/R_d$ of five SCs selected from those with $m_{sc} < 2 \times 10^5 M_\odot$ (lower) and from those with $m_{sc} \geq 2 \times 10^5 M_\odot$ (upper) in the standard model. Owing to dynamical influences of a stellar bar and spiral arms on SCs and SC-SC mutual interaction, $R/R_d$ of these SCs can evolve in a complicated way.

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Figure A1. Time evolution of $R/R_d$ of five SCs selected from those with $m_{sc} < 2 \times 10^5 M_\odot$ (lower) and from those with $m_{sc} \geq 2 \times 10^5 M_\odot$ (upper) in the standard model.
Owing to dynamical interaction between the non-axisymmetric structures (e.g., bar and spiral arms) developed in the later phase of the disk’s dynamical evolution, orbital evolution of these SCs can be quite complicated. One example of this is that not all of the SCs show significant declines in $R$ owing to dynamical friction within $\sim 0.6$ Gyr. Some of SCs show orbital decay before the formation of a stellar bar, their $R$ can again become larger after the bar formation owing to redistribution of angular momentum by the bar. It appears that SC-SC interaction does not play a vital role in the orbital evolution of SCs owing to the small number ($=20$) of SCs in this model.