DISSIPATIVE TRANSFORMATION OF NONNUCLEATED DWARF GALAXIES INTO NUCLEATED SYSTEMS

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ABSTRACT

Recent photometric observations by the Hubble Space Telescope have revealed the physical properties of stellar galactic nuclei in nucleated dwarf galaxies in the Virgo cluster of galaxies. In order to elucidate the formation processes of nucleated dwarfs, we numerically investigate gasdynamics, star formation, and chemical evolution within the central 1 kpc of gas disks embedded within the galactic stellar components of nonnucleated dwarfs. We find that high-density, compact stellar systems can be formed in the central regions of dwarfs as a result of dissipative, repeated merging of massive stellar and gaseous clumps developed from nuclear gaseous spiral arms as a consequence of local gravitational instability. The central stellar components are found to have stellar masses that are typically 5% of their host dwarfs’ and show very flattened shapes, rotational kinematics, and central velocity dispersions significantly smaller than those of their host dwarfs. We also find that more massive dwarfs can develop more massive, more metal-rich, and higher density stellar systems in their central regions, because star formation and chemical enrichment proceed more efficiently owing to the less dramatic suppression of star formation by supernova feedback effects in more massive dwarfs. Based on these results, we suggest that gas-rich, nonnucleated dwarfs can be transformed into nucleated ones as a result of dissipative gasdynamics in their central regions. We discuss the origin of the observed correlations between physical properties of stellar galactic nuclei and those of their host galaxies.

Subject headings: galaxies: dwarf — galaxies: star clusters — globular clusters: general

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1. INTRODUCTION

A growing number of photometric studies of dwarf galaxies by the Hubble Space Telescope (HST) have recently revealed the physical properties of stellar galactic nuclei of dwarfs in the Virgo cluster of galaxies (e.g., De Propris et al. 2005; Grant et al. 2005; Haşegan et al. 2005). HST photometric observations have also revealed that a significant fraction of late-type galaxies have very compact stellar systems in their very centers (Phillips et al. 1996; Carollo et al. 1998; Matthews et al. 1999; Böker et al. 2004; Walcher et al. 2005). The physical properties of stellar galactic nuclei (e.g., mass and surface brightness) have been suggested to be correlated with those of their host galaxies (Böker et al. 2004). Spectrophotometric studies of nucleated dwarf galaxies have revealed the structural and kinematic properties of their central stellar components (e.g., Stiavelli et al. 2001; Geha et al. 2002; Lotz et al. 2004).

Although these recent observations, combined with previous ones on nucleated dwarfs (e.g., Bingelli & Cameron 1991; Ferguson & Bingelli 1994), have provided vital clues to understanding the formation of nucleated dwarf elliptical (dE,N) and irregular (dI,N) galaxies, only a small number of theoretical works have so far investigated the formation processes of their stellar galactic nuclei (e.g., Tremaine et al. 1975; Oh & Lin 2000; Bekki et al. 2004). One of the most extensively discussed scenarios is that these stellar nuclei are formed from the merging of smaller stellar clusters of globular cluster–like mass in the central regions of galaxies (e.g., Oh & Lin 2000; Bekki et al. 2004). These numerical works, which are based on dissipationless models of merging star clusters, have provided some predictions for the structural and kinematic properties of stellar nuclei. These previous works, however, did not at all discuss how gaseous dissipation and star formation are important in the formation of nucleated dwarfs, even though a number of spectrophotometric observations have already provided possible evidence of very young stellar populations in the stellar nuclei of some nucleated galaxies (e.g., Caldwell & Bothun 1987).

The purpose of this Letter is thus to demonstrate, for the first time, that gaseous dissipation and star formation can play a vital role in the formation of nucleated dwarfs (i.e., dE,N’s and dI,N’s). Based on the results of chemodynamical simulations of the gasdynamics and star formation within the central 1 kpc of nonnucleated dwarfs, we demonstrate that nonnucleated dwarfs can be transformed into nucleated ones as a result of dissipative nucleation. We investigate the structural, kinematic, and chemical properties of stellar galactic nuclei in nucleated dwarfs with different masses and gas mass fractions and thereby provide theoretical predictions that can be tested against recent observations. Although the present study suggests the importance of gas clump formation in inward mass transfer processes for dwarfs, this importance has already been proposed by Shlosman & Noguchi (1993) and Noguchi (1999) in the context of triggering mechanisms of starbursts and bulge formation.

2. THE MODEL

We investigate the dynamical evolution of stellar and gaseous components within the central 1 kpc of a galaxy, using chemodynamical simulations carried out on a GRAPE board (Sugimoto et al. 1990). Since the numerical methods and techniques we use for the GRAPE system have already been described in detail elsewhere (Bekki & Shioya 1999), we give only a brief review here.
Old stellar components of dwarf galaxies (dI’s and dE’s) are observed to have exponential luminosity profiles (e.g., Ichikawa et al. 1986), and therefore the projected radial density profile of the stellar component, with mass $M_{\text{sph}}$ and scale length $a_{\text{sph}}$, is assumed to be an exponential one with the central surface density of $\Sigma_{\text{sph},0}$. Guided by recent observations on the scaling relation between $\Sigma_{\text{sph},0}$ and $M_{\text{sph}}$ (i.e., $\Sigma_{\text{sph},0} \propto M_{\text{sph}}^{0.54}$; Kauffmann et al. 2003), we adopt the $M_{\text{sph}}$-$a_{\text{sph}}$ relation $a_{\text{sph}} = C_0 M_{\text{sph}}^{0.23}$, where $C_0$ is chosen such that the mass and the scale length of the Galactic exponential bulge can be reproduced reasonably well. For example, this equation gives $a_{\text{sph}} = 200$ pc for $M_{\text{sph}} = 10^9 M_\odot$.

The gas disk in a dwarf is modeled as a collection of discrete gas clouds with the observed mass-size relationship of giant molecular clouds (Larson 1981). The thin gas disk composed of these clouds is assumed to have an exponential profile, with the scale length being the same as $a_{\text{sph}}$. The mass ratio of the gas disk to the initial stellar component is regarded as a free parameter ($f_\text{s}$) that ranges from 0.02 to 0.5. Every pair of two overlapping gas clouds is made to collide with the same restitution coefficient (Hausman & Roberts 1984) and lose its random kinetic energy through gaseous dissipation.

Field star formation is modeled by converting the collisional gas particles into collisionless, new stellar particles according to the algorithm for star formation described below. We adopt the Schmidt law (Schmidt 1959) with exponent $\gamma = 1.5$ ($1.0 < \gamma < 2.0$; Kennicutt 1998) as the controlling parameter of the rate of star formation. These stars formed from gas are called “new stars” (or “young stars”), whereas stars initially within a spheroid are called “old stars,” throughout this Letter. Chemical enrichment through star formation and supernova feedback during the stellar nucleus formation and evolution is assumed to proceed locally, and the values of the return parameter and the chemical yield are set to be 0.3 and 0.005, respectively. About 10% of the total energy of one Type II supernova ($\sim 10^{51}$ ergs) is assumed to be converted into kinematic energy of gas around the supernovae (Thornton et al. 1998) for the Salpeter initial mass function. The feedback effects are stronger in low-mass dwarfs for the adopted mass-size relation in the present study.

We mainly investigate projected radial density profiles ($\mu_\text{sph}$) of new and old stars in the central regions of spheroids. In order to compare the simulated profiles ($\mu_\text{sph}$) with the observed $B$-band surface brightness profiles ($\mu_\text{obs}$), we use the formula $\mu_\text{obs} = 27.05 - 2.5 \log I_\text{sph}$, where $I_\text{sph}$ is the $B$-band surface brightness of a stellar system measured in units of $L_\odot$ pc$^{-2}$. We estimate $I_\text{sph}$ from $\mu_\text{sph}$ for a given mass-to-light ratio ($M/L_\text{sph}$) in the $B$ band. We assume that $M/L_\text{sph}$ for old stars ($M/L_\text{sph,old}$) is 10, corresponding to a single stellar population (SSP) with age 10 Gyr and solar metallicity (Vazdekis et al. 1996), and that for new stars, ($M/L_\text{sph,new}$), is 0.5, corresponding to an SSP with age 0.5 Gyr and solar metallicity.

We first describe the results of the fiducial model with $M_{\text{sph}} = 10^9 M_\odot$ and $f_\text{s} = 0.2$, which shows typical behavior of dissipative nucleus formation in dwarfs. Then we describe briefly the dependences of the results on $M_{\text{sph}}$ and $f_\text{s}$. The details of the parameter dependences (including those on $M/L_\text{sph}$) will be given in forthcoming papers. The total number of particles is $10^5$ for the old stars ($N_\text{old}$) and $2 \times 10^4$ for the initial gas ($N_\text{gas}$), and the time integration of the equation of motion is performed by using the second-order leapfrog method.

Figure 1 shows how a compact stellar system is formed in the central region of the star-forming gas disk embedded in the old stellar spheroid for the fiducial model. Numerous spiral arms composed only of gas clouds first develop owing to the stronger self-gravity of gas ($f_\text{s} = 0.2$) as the gas disk rotates ($T = 62$ Myr). Because of the enhanced cloud-cloud collision rate and the resultant efficient gaseous dissipation within the gaseous spiral arms, small gas clumps composed of several tens of gas clouds can be formed within each spiral arm ($T = 250$ Myr). Some of these small gaseous clumps are...
The stellar nucleus shows a significant amount of rotation (20–30 km s\(^{-1}\)) within the central 100 pc (and thus within the central region of the stellar spheroid). Although the single nucleus is initially not in the very center of the spheroid, dynamical friction between the nucleus and the stellar background can finally transfer the nucleus into the mass center of the spheroid within \(\sim 100\) Myr. Thus a stellar nucleus (which can be regarded as stellar nuclei) on one hand, and a normal spheroid on the other hand, are investigated in the present study. The dependences of the physical properties of the compact stellar systems (which can be regarded as stellar nuclei) on \(M_{\text{ sph}}\) and \(f_{\text{s}}\) can be briefly summarized as follows: First, the total mass of the stellar nuclei \((M_{\text{nuc}})\) in units of \(M_{\odot}\) within 50 pc (5\% of an initial gas disk size) is correlated with the initial stellar masses \((M_{\text{ sph}})\), and this correlation can be described as \(M_{\text{nuc}} = 0.046M_{\text{ sph}}^{-0.0030}\).

Figure 4 clearly shows that the more metal-rich stars are also more likely to be younger. Models with different \(M_{\text{ sph}}\) (2.5 \(\times\) 10\(^6\), 1.0 \(\times\) 10\(^6\), 3.0 \(\times\) 10\(^6\), and 1.0 \(\times\) 10\(^7\) \(M_{\odot}\)) and different \(f_{\text{s}}\) (0.02, 0.05, 0.2, and 0.5) are investigated in the present study. The dependences of the physical properties of the compact stellar systems (which can be regarded as stellar nuclei) on \(M_{\text{ sph}}\) and \(f_{\text{s}}\) can be briefly summarized as follows: First, the total mass of the stellar nuclei \((M_{\text{nuc}})\) in units of \(M_{\odot}\) within 50 pc (5\% of an initial gas disk size) is correlated with the initial stellar masses \((M_{\text{ sph}})\), and this correlation can be described as \(M_{\text{nuc}} = 0.046M_{\text{ sph}}^{-0.0030}\).
Here we apply a least-squares fit to the results of the models that have different $M_{\text{nuc}}$ and clearly show stellar nucleus formation. If we make a least-squares fit to the log $M_{\text{nuc}}$–log $M_{\text{sph}}$ relation, we can derive the relation log $M_{\text{nuc}} = 1.1 \log M_{\text{sph}} - 2.5$. Second, the mass fraction of the stellar nucleus ($f_{\text{nuc}}$) in nucleated dwarfs is correlated with $M_{\text{sph}}$, and the correlation can be described as $f_{\text{nuc}} = 0.021[M_{\text{sph}}/(10^9 M_{\odot})] + 0.023$. Third, the metallicities of stellar nuclei are higher than those of their host galaxies in most models. Accordingly, stellar nuclei can be significantly redder than their host galaxies after significant aging of their stellar populations. More massive dwarfs can have more metal-rich stellar nuclei.

Fourth, stellar nuclei do not develop within a few Gyr in the models with smaller $f_{\text{nuc}} (<0.05)$, which strongly suggests that the self-gravity of gas is quite an important factor for dissipative formation of stellar nuclei. The central surface brightness ($\mu_0$) of stellar nuclei is higher in models with higher $f_{\text{nuc}}$, which implies that the observed diversity in $\mu_0$ between different dwarfs (see, e.g., De Propris et al. 2005) can be understood in terms of a different amount of gas within the dwarfs. Fifth, dense stellar nuclei are more likely to develop in dwarfs with higher stellar densities, owing to their deeper gravitational potentials (i.e., weaker supernova feedback effects).

**4. DISCUSSION AND CONCLUSIONS**

It has long been known that more luminous dwarf galaxies (dE's) are more likely to contain stellar nuclei (e.g., van den Bergh 1986): the number fraction of dE,N's among dE's is almost 100% for $M_B \approx -18$ mag and about 20% for $M_B \approx -12$ mag. The present simulations demonstrate that less luminous galaxies can have less remarkable stellar nuclei and that some stellar nuclei can hardly be identified observationally as distinct nuclei. They also suggest that the origin of this dependence is closely associated with the fact that the stellar nucleus formation is more strongly suppressed by stronger feedback effects in less luminous galaxies. These simulation results suggest that the origin of the observed dependence of the dE,N fraction on the host luminosities can be understood in terms of the luminosity (or mass) dependence of the effectiveness of supernova feedback in stellar nucleus formation.

Recently, Lotz et al. (2004) have uncovered the fact that some stellar nuclei of dE,N’s have colors that are significantly bluer than those of their host galaxies and could be due to recent star formation episodes. Several previous spectroscopic observations of stellar nuclei in dE,N’s have also revealed possible evidence of younger stellar populations in these stellar nuclei (e.g., Caldwell & Bothun 1987; Bothun & Mould 1988). The present study suggests that if these apparently young stellar nuclei were formed dissipatively from gas as our simulations have demonstrated, they should be significantly more metal-rich than their host galaxies. It is thus doubtlessly worthwhile for future spectroscopic observations to investigate the metallicity differences between stellar nuclei and their host galaxies.

We have demonstrated that gasdynamics and star formation in the central 1 kpc of dwarfs can be important for the transformation of nonnucleated dwarfs into nucleated systems. One of the advantages of the dissipative nucleus formation scenario is that it can naturally explain how massive stellar and gaseous clumps, which are “building blocks” of stellar nuclei, can be formed in the central regions of gas-rich dwarfs. This scenario, however, has not yet provided clear explanations for some of the key observed correlations between dynamical properties of stellar nuclei and those of their host galaxies (e.g., Böker et al. 2004).

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