No. ______

国立天文台 天文学データ解析計算センター
成果報告書 (平成16年度)

提出期限：平成17年3月14日(月)17:00必着

応募カテゴリ（いずれかを選択）　A ・(B)・ C
システム（いずれかを選択）　VPP ・(GRAPE)

プロジェクトID: g04b02

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研究課題名

(和文) 銀河団銀河の化学力学数値シミュレーション
(英文) Chemodynamical simulations of cluster galaxies

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成果に関連して出版、もしくは印刷、投稿中の論文リスト

(1) このプロジェクト（同様の過去のプロジェクトも含む）での成果

今年度中に出版された論文、国際会議集録、国際会議、学会、研究会発表、その他出版物（印刷中、投稿中の場合はその旨を記載すること）

Bekki, Kenji, Couch, Warrick J., Drinkwater, Michael J., & Shioya, Yasuhiro 2004, ApJ, 610, L13 (July 2004), "Cluster Cannibalism and Scaling Relations of Galactic Stellar Nuclei"

Bekki, Kenji, Couch, Warrick J., Vazdekis, Alexandre, & Shioya, Yasuhiro 2005, MNRAS, in press, "Origin of E+A galaxies: I. Physical properties of E+A's formed from galaxy merging and interaction"

(2) これまでのプロジェクトの今年度中の成果

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成果の概要

(必要に応じてページを加えて下さい。)

本年度は (i) Fornax cluster で最近発見された ultra-compact dwarf galaxies (UCDs) と late-type galaxies の nuclear star clusters (NCs) との間の進化的な関係、および (ii) 銀河団銀河で特徴的に見られると考えらている E+A galaxies が galaxy merger で形成されると考えたときのその形成と進化の過程、についてシミュレーションを行い、上記の論文として公表した (後者は in press)。

得られた結果の詳細については別紙参照。

Chemodynamical simulations of cluster galaxies

Yasuhiro Shioya (Tohoku University), Kenji Bekki (UNSW) &
W. J. Couch (UNSW)

1 Introduction

We numerically investigated (1) evolutionary links between ultra-compact dwarf galaxies (UCDs) discovered in clusters and nuclear star cluster (NCs) in late-type galaxies and (2) formation and evolution of E+A's formed by galaxy merging this year. In this report, we describe numerical results obtained in these two investigation and provide some observations implications of the results. These two sets of numerical simulation results are/will be published (Bekki et al. 2004, ApJ, 610, L13; Bekki et al. 2005, accepted in MNRAS).

2 Evolutionary links between UCDs and NCs

2.1 Formation of stellar galactic nuclei via cluster mergers

A new type of sub-luminous and extremely compact "dwarf galaxy" has been recently discovered in an 'all-object' spectroscopic survey centered on the Fornax Cluster (Drinkwater et al. 2000). These "dwarf galaxies", which are members of the Fornax Cluster, have intrinsic sizes of less than 100 pc and absolute B band magnitude ranging from -13 to -11 mag and are thus called "ultra-compact dwarf" (UCD) galaxies. Although these UCDs are suggested to originate from stellar nuclei of bright nucleated dwarf galaxies (Drinkwater 2000; Bekki et al. 2001, 2003), it is unclear how such massive nuclei are formed in the central region of dwarf galaxies.

Recent *Hubble Space Telescope* (HST) photometric observations have discovered very luminous nuclear clusters (NCs), with I-band absolute magnitudes ($M_{\rm I}$) ranging from -8 to -14 mag, in the central regions of late-type spirals (Phillips et al. 1996; Carollo et al. 1998; Matthews et al. 1999; Böker et al. 2002, 2004a,b). The observation that some of the bright NCs are quite massive – that is their luminosity does not derive from a small number of hot young stars – has raised the question as to how such massive NCs can be formed in the central regions of late-type spiral galaxies (Böker et al. 2004a,b).

In order to understand the formation processes of UCDs and NCs (very massive star clusters, VMSCs), we investigate the dynamical evolution of a self-gravitating system composed of smaller star clusters (SCs), via numerical simulations carried out on a GRAPE board (Sugimoto et al. 1990). Each of the individual SCs that merge with one another to form a VMSC, are assumed to have a Plummer density profile (e.g., Binney & Tremaine 1987) with luminosities ($L_{\rm sc}$) and central velocity dispersions ($\sigma_{\rm sc}$) consistent with the relation observed for GCs (Djorgovski et al. 1997):

$$L_{\rm sc} \propto {\sigma_{\rm sc}}^{1.7}. \tag{1}$$

The scale length ($a_{\rm sc}$) of a SC is determined by the formula

$$a_{\rm sc} = GM_{\rm sc}/6{\sigma_{\rm sc}}^{2}, \tag{2}$$

where G and $M_{\rm sc}$ are the gravitational constant and the mass of the SC, respectively (More details can be found in our paper, Bekki et al. 2004, ApJ, 610, L13). We investigate structural and kinematical properties of these merger remnants of SCs. We mainly describe the equal-mass 3D model with $N_{\rm sc}$ = 12 (the "fiducial" model), because this model shows both typical behavior of VMSC formation and one of the most interesting results in the present study. The mass, length, time, and velocity units are 2.0×10^6 $M_{\odot}$, 34.0 pc, 2.1×10^6 yr, and 15.9 km s^{-1}.

2.2 Simulation results

As seen from the fiducial model shown in Figure 1, smaller SCs repeatedly merge with one another to form bigger clusters through the process of dynamical collapse of the SC system. These bigger clusters then merge to form a single VMSC with an outer diffuse stellar envelope, within $\sim 10^7$ yr. The VMSC has an effective radius ($R_{\rm e}$) of 19.4 pc (2.85 $R_{\rm e}$ of the progenitor SC) and within $5R_{\rm e}$ a mass of 2.1×10^7 $M_{\odot}$, which corresponds to $M_{\rm V} = -12.9$ mag and is 10.2 times more massive than the mass of the original SCs.

Figure 2 shows the comparison between the locations of all of the simulated VMSCs in the $M_{\rm V} - \sigma_0$ plane and the corresponding observations (Drinkwater et al. 2003). Here only (5) UCD points are plotted, since data for NCs is not available. The locations of the simulated brighter VMSCs are consistent with the observations, and both the simulated and observed data points are closer to the Faber-Jackson relation than to the $M_{\rm V} - \sigma_0$ relation of GCs (Djorgovski et al. 1997). This implies that the origin of UCDs' structural and kinematically properties is significantly different to that of GCs, and is closely associated with physics of multiple merging of SCs. Thus the present results on the scaling relations of VMSCs clearly show that the scaling relations of VMSCs formed from multiple SC merging are significantly different both from those of their progenitor SCs (or GCs) and from those of dynamically hot early-type galaxies.

2.3 Discussions and conclusions

We have demonstrated that if VMSCs are formed from the multiple merging of SCs, with the observed scaling relations of GCs, the scaling relations of VMSCs are very different from those of GCs. Ongoing and future photometric and spectroscopic observations (e.g., *HST* ACS and Keck 10m) of the structural and

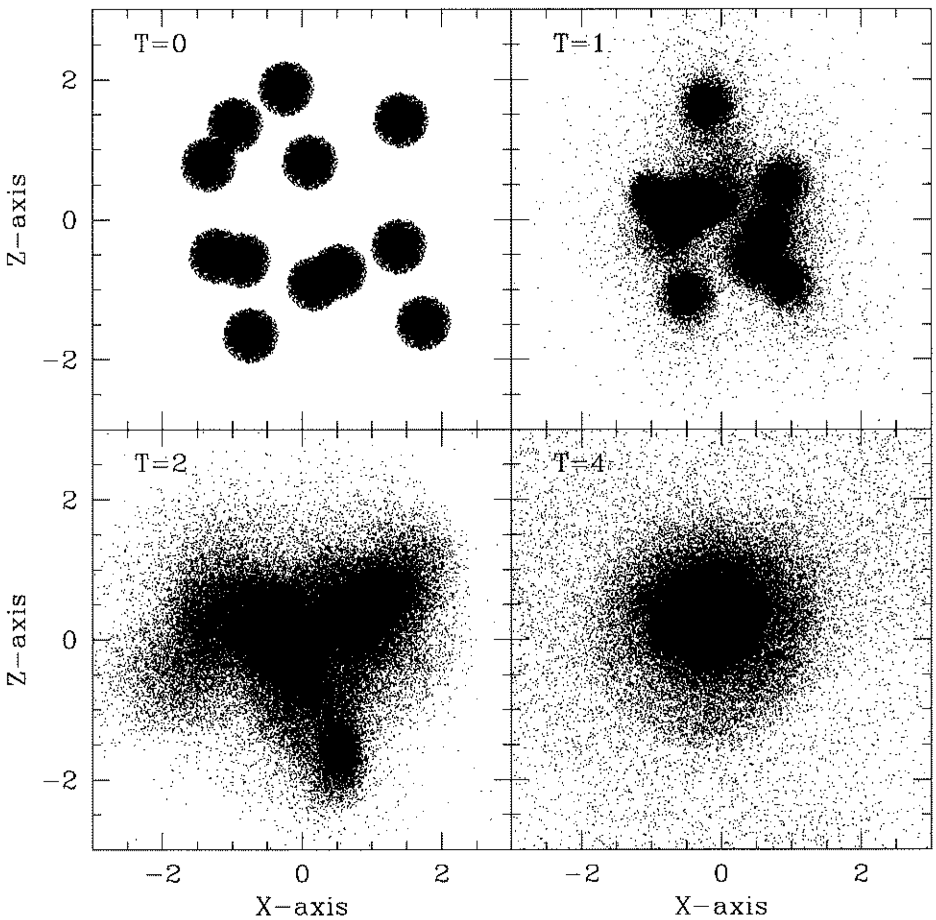

Figure 1: Morphological evolution of twelve equal-mass star clusters (SCs) projected onto the $x - z$ plane for the fiducial model (with an initial total mass of $2.4 \times 10^7\ M_{\odot}$). The length and the time are given in our units (34.0 pc and 2.1 $\times\ 10^6$ yr, respectively). Here the time T represents the time that has elapsed since the start of the simulation.

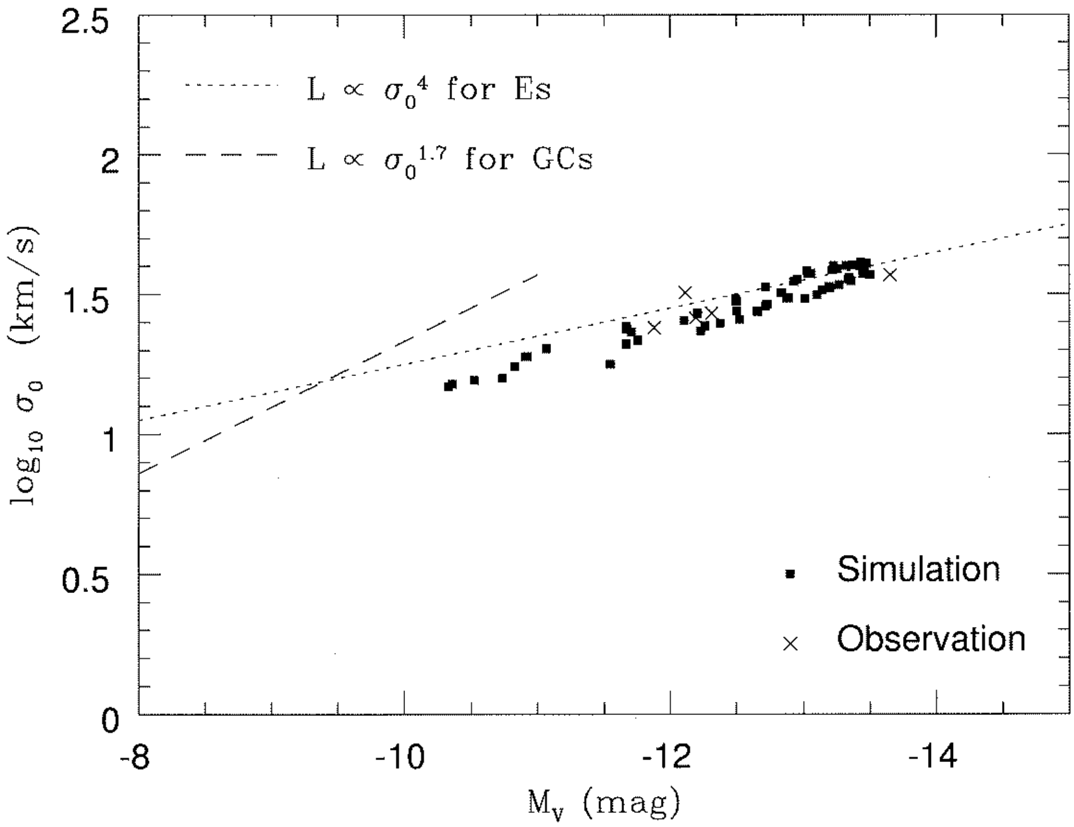

Figure 2: Correlations of σ_0 with M_V for the simulated VMSCs (*filled squares*) and the observations (*crosses*). The results of 60 models, including both equal-mass 2D/3D models and multi-mass ones, are shown. Only 5 UCDs with known σ_0 (Drinkwater et al. 2003) are plotted (no velocity dispersion data for NCs are available). For comparison, the observed relations are given by a *dashed* line for GCs (Djorgovski et al. 1997) and a *dotted* line for Es (Faber & Jackson 1976).

kinematical properties of VMSCs will therefore be able to assess the viability of the "cluster cannibalism" scenario of stellar nucleus formation.

Although we have not discriminated between UCDs and NCs in this report, there exists a possible remarkable difference in the size distribution between the two: The observed effective radii range from 15 pc to 30 pc for UCDs and from 2.4 pc to 5 pc for NCs. This difference can possibly be ascribed to the young stellar populations with compact spatial distributions within NCs (i.e., the size distributions for old populations of NCs could not be so different from those of UCDs). However, it is equally possible that the difference is due to the differences in formation processes between UCDs and NCs. Differences in scaling relations between UCDs and NCs, if any, would tell us something about the origin of the difference between UCDs and NCs.

3 Origin of E+A's

3.1 Why "spectrodynamical simulations" ?

Recent high resolution imaging, photometric and spectroscopic studies of E+A galaxies undertaken with the *Hubble Space Telescope* (*HST*) and large ground-based telescopes have revealed a considerable diversity in the morphological, structural, and kinematical properties between E+A's (Norton et al. 2001; Yang et al. 2004). For example, Norton et al. (2001) investigated the internal kinematics of the E+A galaxies in the Z96 sample and found that most of them were dynamically supported, with v/σ and σ ranging from $30\,\mathrm{km\,s^{-1}}$ to $200\,\mathrm{km\,s^{-1}}$ (here v is the rotational velocity and σ is the velocity dispersion). This plethora of observational data on E+A galaxies, when taken in its entirety, raise many questions, the most significant being: (i) Can model(s) of galaxy interactions and merging (e.g., minor vs major merging) explain *self-consistently* the observed dynamical, photometric, and spectroscopic properties of E+A's?. (ii) What mechanism drives the formation of disky E+A's that dominates E+A populations in clusters of galaxies? (iii) What is the origin of the positive and negative color gradients observed in E+A's? (iv) Are there any differences between the structural and kinematical properties of the old and young stellar populations in E+A galaxies? Although previous theoretical studies have tried to understand possible star formation histories of E+A galaxies (Barbaro & Poggianti 1997; Poggianti et al. 1999; Shioya & Bekki 2000; Shioya et al. 2002; 2004), they had difficulty in addressing the above questions due to the limitations of the one-zone spectrophotometric models that they adopted. In order to properly tackle the above questions, the dynamical and spectrophotometric properties of E+A galaxies need to be investigated *jointly* in an explicitly self-consistent manner. **Therefore, numerical simulations combined with stellar population synthesis codes – which enable us to predict not only structural and kinematical properties but also photometric and**

spectroscopic ones – are indispensable in solving the above important problems related to the formation and evolution of E+A galaxies.

3.2 Results: 2D spectral distributions

We investigate the structural, kinematical, chemical, photometric, and spectroscopic properties of E+A galaxies in an explicitly self-consistent manner, thereby making considerable progress toward answering the above question. In particular, we investigate both *radial gradients* in the spectrophotometric properties as well as the *projected* (2D) distributions of Balmer absorption, rotational velocity and velocity dispersion in E+A galaxies formed from galaxy interactions and merging. Since the details of our spectrodynamical models are given in Bekki et al. (2005, MNRAS in press), we here describe one of the main results.

The star formation histories, which determine the final spectrophotometric properties of the remnant interacting/merging galaxies, differ quite significantly in our simulations, being dependent on the gas mass fraction ($f_{\rm g}$), the bulge-mass fraction ($f_{\rm b}$), and the mass ratio of the merging two disks (m_2). Figure 3 shows an example of this dependence. The structural and kinematical properties of the simulated E+A's are also diverse, depending mainly on m_2 and the orbital configurations. We however describe only one result from our most representative model which show the typical and/or most interesting behavior in E+A formation and evolution.

Figure 4 clearly shows that the 2D distributions of EW(Hδ) and EW(Hβ) absorption have very flattened shapes along the z-axis, and the direction of elongation is coincident with the major axis of the mass distribution of young stars with EW(Hδ) $>$ 6Å(shown in Fig. 4). It also shows that both EW(Hδ) and EW(Hβ) are larger in the inner regions of the E+A, and therefore have a negative radial gradients. These results are all due principally to the centralized starbursts during dissipative merging in this model. The flattened 2D distribution can also be seen in the optical ($V - I$) and near-infrared ($I - K$) color distributions, which confirms that the flattened shape is due to the flattened distribution of young stars in the core of the E+A's.

3.3 Summary of the simulation results

Because of the page limitation of this report, we here summarize the most important three results obtained in this GRAPE project on E+A formation.

(1) E+A ellipticals formed by dissipative major galaxy merging show positive radial gradients in color (i.e., bluer colors at their center) and negative radial gradients in Balmer absorption line strength, due to the larger fraction of A-type stars in their inner regions. These color and line index gradients become shallower as time passes by, because of the aging of the poststarburst stellar population. These numerical models, however, cannot explain the E+A galaxies

that are observed to have negative radial gradients in both color and Balmer absorption line strength.

(2) The dynamical and spectroscopic properties of E+A ellipticals formed by dissipative major galaxy merging have 2D distributions which can be remarkably different, depending on the orbital parameters of the merger. Furthermore, such differences also exist between the old and young stars in these galaxies. For example, E+A ellipticals with kinematically decoupled cores (KDC's) have a very flattened Hδ absorption distribution, with differences in rotation and velocity dispersion between the old and young stars. Future spatially resolved, integral field unit spectroscopy with 8-10m class telescopes should be able to bring the past KDC formation sites in young E+A ellipticals into relief and thus provide an evidence that KDCs can be formed from dissipative major merging.

(3) The 2D distributions of colors and Balmer absorption lines in E+A ellipticals show a larger internal dispersion compared with those of 'passive' ellipticals with weak Hδ ($\sim$0Å). The internal color dispersion of ellipticals formed by major merging becomes smaller as the E+A phase passes, and therefore there will be an anti-correlation between the size of this dispersion and Hδ strength in the post-E+A phase. These results imply that the large color dispersion in the 2D photometric properties of E+A ellipticals provides further evidence for the transformation from gas-rich late-type spirals into passive ellipticals.

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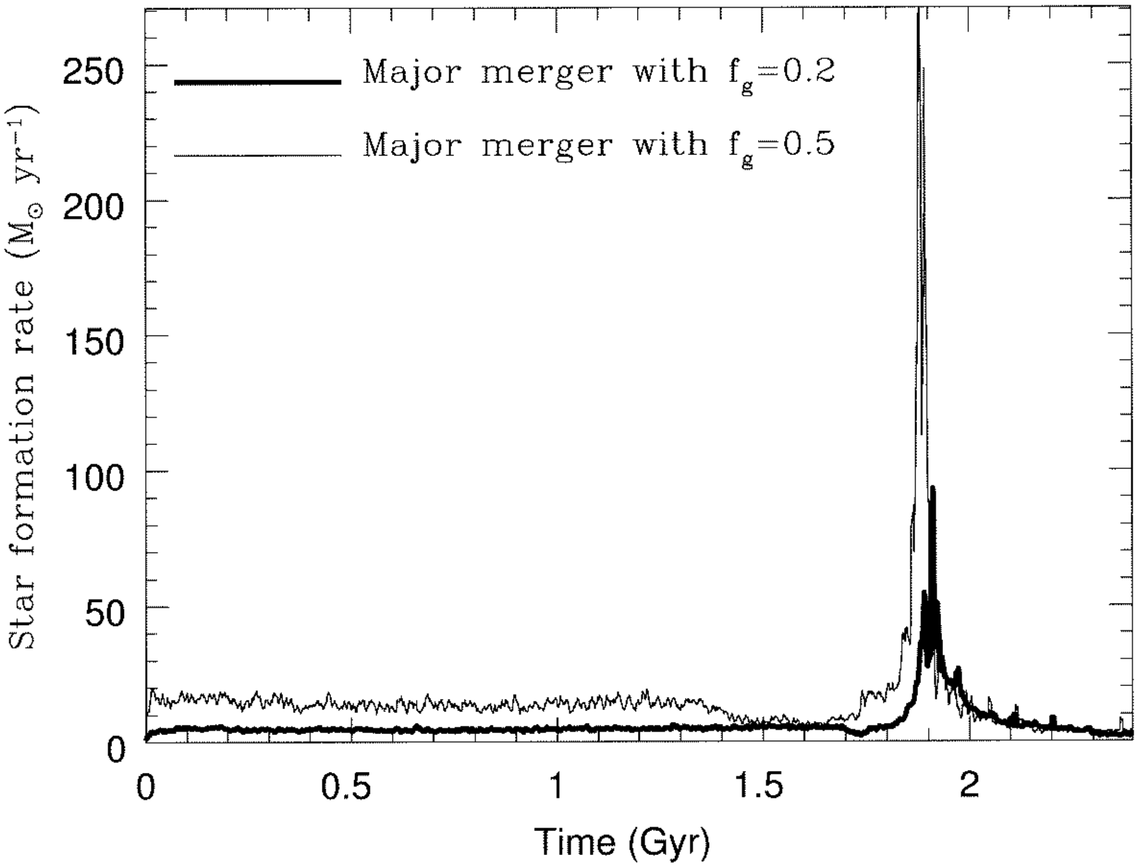

Figure 3: Star formation histories of major galaxy mergers between gas-rich spirals for the model with $f_g = 0.2$ (*thin solid*) and the model with $f_g = 0.5$ (*thick solid*) for 2.4 Gyr. These two models are examples of merger-driven massive starbursts with a subsequent rapid decline in star formation rate.

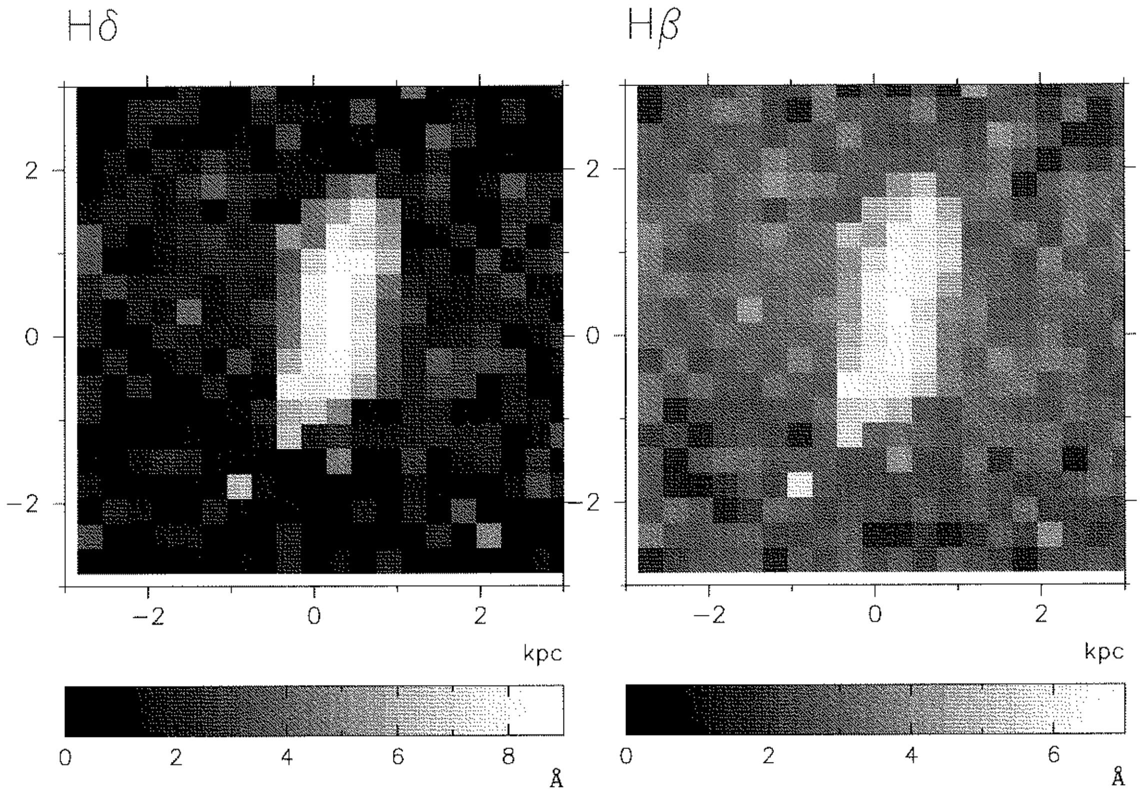

Figure 4: The two-dimensional (2D) distributions of EW(Hδ) (*left*) and EW(Hβ) (*right*) projected onto the x-z plane in the major merger model at $T = 2.8$ Gyr. The abscissa and the ordinate represent the x-axis and the z-axis, respectively. Here we divide the 3 kpc × 3 kpc central region into 20 × 20 grid points and thereby estimated the SED of each grid point. For clarity, the grid points with EW(Hδ) (and EW(Hβ)) less than 0Å are shown in the darkest color. Note that the 2D distributions show the strong Balmer line absorption to be elongated along the z-axis.

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THE ASTROPHYSICAL JOURNAL, 610:L13–L16, 2004 July 20

CLUSTER CANNIBALISM AND SCALING RELATIONS OF GALACTIC STELLAR NUCLEI

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Received 2004 May 12; accepted 2004 June 7; published 2004 June 22

ABSTRACT

Recently, very massive compact stellar systems have been discovered in the intracluster regions of galaxy clusters and in the nuclear regions of late-type disk galaxies. It is unclear how these compact stellar systems—known as "ultracompact dwarf" (UCD) galaxies or "nuclear clusters" (NCs)—form and evolve. By adopting a formation scenario in which these stellar systems are the product of multiple merging of star clusters in the central regions of galaxies, we investigate, numerically, their physical properties. We find that physical correlations among velocity dispersion, luminosity, effective radius, and average surface brightness in the stellar merger remnants are quite different from those observed in globular clusters. We also find that the remnants have triaxial shapes with or without figure rotation, and these shapes and their kinematics depend strongly on the initial number and distribution of the progenitor clusters. These specific predictions can be compared with the corresponding results of ongoing and future observations of UCDs and NCs, thereby providing a better understanding of the origin of these enigmatic objects.

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

1. INTRODUCTION

A new type of subluminous and extremely compact "dwarf galaxy" has been recently discovered in an "all-object" spectroscopic survey centered on the Fornax Cluster (Drinkwater et al. 2000). These dwarf galaxies, which are members of the Fornax Cluster, have intrinsic sizes of less than 100 pc and absolute B-band magnitude ranging from -13 to -11 mag and are thus called "ultracompact dwarf" (UCD) galaxies. Although these UCDs are suggested to originate from stellar nuclei of bright nucleated dwarf galaxies (Drinkwater et al. 2000; Bekki et al. 2001, 2003), it is unclear how such massive nuclei are formed in the central region of dwarf galaxies.

Recent *Hubble Space Telescope* (*HST*) photometric observations have discovered very luminous nuclear clusters (NCs), with I-band absolute magnitudes (M_I) ranging from -8 to -14 mag, in the central regions of late-type spirals (Phillips et al. 1996; Carollo et al. 1998; Matthews et al. 1999; Böker et al. 2002, 2004a, 2004b). The observation that some of the bright NCs are quite massive—that is, their luminosity does not derive from a small number of hot young stars—has raised the question as to how such massive NCs can be formed in the central regions of late-type spiral galaxies (Böker et al. 2004a, 2004b).

One formation scenario for these very massive star clusters (VMSCs) is that ordinary star clusters (SCs), which can quickly spiral into the nuclear regions of galaxies because of dynamical friction, merge with one another to form a single VMSC (i.e., galactic stellar nuclei; Tremaine et al. 1975). The physical properties of VMSCs formed in this way, however, have not been theoretically/numerically investigated extensively (e.g., Fellhauer & Kroupa 2002). In particular, theoretical predictions of the correlations between their structural and kinematical properties (e.g., central velocity dispersion) are generally considered to be important, because such dynamical correlations (or "scaling relations") for a self-gravitating system are generally considered to help discriminate between different formation mechanisms (e.g., Djorgovski 1993). In the light of recent discoveries of UCDs and NCs, it is thus timely and important to discuss whether such a merger scenario (referred to as "cluster cannibalism" in galactic nuclei) is consistent with their observed properties.

The purpose of this Letter is to provide the first theoretical predictions on the structural and kinematical properties of VMSCs formed by *dissipationless* multiple cluster merging based on self-consistent numerical simulations of nucleus formation. We focus particularly on correlations among properties such as luminosity (L), effective radius (R_e), central velocity dispersion (σ_0), and surface brightness at R_e. The predicted scaling relations combined with current and future observations of UCDs (e.g., Drinkwater et al. 2003) and NCs (e.g., Böker et al. 2004a, 2004b) can provide new insight into the origin of galactic stellar nuclei. Dissipative formation, which is an alternative formation scenario for VMSCs (Böker et al. 2004a, 2004b), will be discussed in forthcoming papers.

2. THE MODEL

We investigate the dynamical evolution of a self-gravitating system composed of smaller SCs, via numerical simulations carried out on a GRAPE board (Sugimoto et al. 1990). Each of the individual SCs that merge with one another to form a VMSC is assumed to have a Plummer density profile (e.g., Binney & Tremaine 1987) with luminosities (L_{SC}) and central velocity dispersions (σ_{SC}) consistent with the relation observed for globular clusters (GCs; Djorgovski et al. 1997):

$$L_{SC} \propto \sigma_{SC}^{1.7}. \quad (1)$$

The scale length (a_{SC}) of an SC is determined by the formula

$$a_{SC} = GM_{SC}/6\sigma_{SC}^2, \quad (2)$$

where G and M_{SC} are the gravitational constant and the mass of the SC, respectively. Since the mass-to-light ratio (M_{SC}/L_{SC}) is assumed to be constant for all SCs, a_{SC} and σ_{SC} are determined by equations (1) and (2) for a given L_{SC} (or M_{SC}). The normalization factor in equation (1) is determined by using the observed typical mass ($6 \times 10^5\ M_\odot$), the half-mass radius (10 pc), and the central velocity dispersion (7 km s^{-1}) for GCs (e.g., Binney & Tremaine 1987).

An SC system is assumed to have either a uniform disk distribution (referred to as two-dimensional models) or a uniform spherical distribution (three-dimensional) and to be fully self-gravitating (i.e., not influenced dynamically by its host galaxy). For the two-dimensional models, an SC system is assumed to have only rotation initially (no velocity dispersion), with its rotational velocity (V_{rot}) at a distance (r) from its center given by

$$V_i(r) = C_V V_{cir}(r), \quad (3)$$

where $V_{cir}(r)$ is the circular velocity at r for this system and C_V is a parameter that determines how far the system deviates from virial equilibrium (i.e., $0 \leq C_V \leq 1$). For three-dimensional models, an SC system is supported only by its random motions; its one-dimensional isotropic dispersion (σ_i) at radius r is given by

$$\sigma_i(r) = C_V \sqrt{-\frac{U(r)}{3}}, \quad (4)$$

where $U(r)$ is the gravitational potential of the system. Here an SC system with $C_V = 1$ means that the system is in virial equilibrium (or supported fully by rotation). We present the results of models in which all of the SCs are within ~100 pc of each other, because they are the most consistent with observations of the structural properties of VMSCs.

We investigate two different representative cases: (1) the SC system is composed only of equal-mass SCs ("equal-mass" case) and (2) the SC system is composed of SCs with different masses ("multimass" case). For (1), each SC is assumed to have a mass of $2 \times 10^6\ M_\odot$ (or $M_V = -10.35$ mag) and $a_{sc} = 6.8$ pc. For (2), the SCs are assumed to have a luminosity (M) function consistent with that observed:

$$\Phi(M) = \text{constant}\, e^{-(M-M_0)^2/2\sigma_m^2}, \quad (5)$$

where $M_0(V) = -7.27$ mag and $\sigma_m = 1.25$ mag (Harris 1991). The number of SCs (N_{SC}) in a system is a free parameter, ranging from 2 to 20 for the equal-mass case and 2 to 200 for the multimass one. The model with the maximum N_{SC} of 200 corresponds to the most massive VMSCs that have been observed (Drinkwater et al. 2003). In our simulation, the masses of the stellar particles in the SCs are assumed to be equal, so that the total number in the simulation depends on N_{SC}. For example, the particle number in the multimass model with $N_{SC} = 200$ is 214,858. We describe the equal-mass three-dimensional model mainly with $N_{SC} = 12$ and $C_V = 0.5$ (the "fiducial" model), because this model shows both typical behavior of VMSC formation and one of the most interesting results in the present study. Also, we describe the (1) scaling relations of the simulated VMSCs and (2) parameter dependences of VMSC properties, based on 60 different models. The mass, length, time, and velocity units are $2.0 \times 10^6\ M_\odot$, 34.0 pc, 2.1×10^6 yr, and 15.9 km s^{-1}.

3. RESULTS

As seen from the fiducial model shown in Figure 1, smaller SCs repeatedly merge with one another to form bigger clusters through the process of dynamical collapse of the SC system.

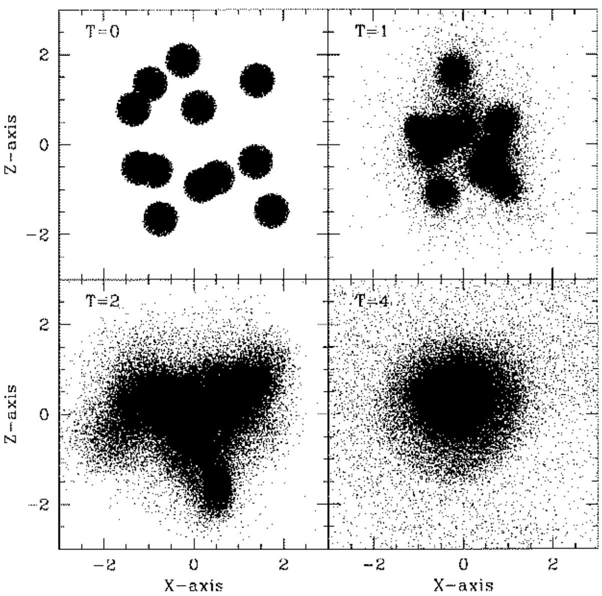

FIG. 1.—Morphological evolution of 12 equal-mass SCs projected onto the x-z plane for the fiducial model (with an initial total mass of $2.4 \times 10^7\ M_\odot$). The length and the time are given in our units (34.0 pc and 2.1×10^6 yr, respectively). Here the time T represents the time that has elapsed since the start of the simulation.

These bigger clusters then merge to form a single VMSC with an outer diffuse stellar envelope, within ~10^7 yr. The VMSC has an effective radius (R_e) of 19.4 pc (2.85 R_e of the progenitor SC) and within $5R_e$ a mass of $2.1 \times 10^7\ M_\odot$, which corresponds to $M_V = -12.9$ mag and is 10.2 times more massive than the mass of the original SCs. Figure 2 shows the structural and kinematical properties of the VMSC. Three different nonspherical shapes can be clearly seen in the three projected mass distributions, which suggests that the VMSC is a triaxial system. The ellipticity (ϵ), defined as $\epsilon = 1 - b/a$, where a and b are the long and the short axes, respectively, in the isodensity contour of the projected mass profile, is estimated to be 0.14 for the x-y projection, 0.08 for the x-z projection, and 0.27 for the y-z projection at the effective radius of the VMSC. Because of efficient conversion of the initial orbital energy of the SCs into internal rotational energy during the SC merging process, the final VMSC has a nonnegligible amount of rotation that is indicated by moderately high V_m/σ_0 (~0.3), where σ_0 and V_m are the central velocity dispersion and the maximum line-of-sight velocity of the VMSC for each projection. It should be noted here that a flattened triaxial system with nonnegligible rotation is remarkably different from typical GCs that have no net rotation and quite spherical shapes (mean $\epsilon = 0.07$; e.g., White & Shawl 1987).

The simulated VMSCs show interesting correlations between their structural and kinematical parameters (Fig. 3). First, more luminous VMSCs have larger central velocity dispersions (σ_0), and this correlation can be expressed as $\sigma_0 \propto L^{0.31}$, the slope of which is similar to that (0.25) of the Faber-Jackson (1976) relation derived for elliptical galaxies. Second, more luminous VMSCs have larger effective radii and the correlation can be expressed as $R_e \propto L^{0.38}$, although the dispersion in this relation is moderately large. This can be compared with the corresponding relation ($R_e \propto L^{1.06}$) derived for elliptical galaxies (Kormendy 1985). Third, L is more strongly correlated with the central surface brightness (I_{10}) than the half-light averaged surface brightness (I_e). Although a single line is fitted to all the data points for the L-I_e

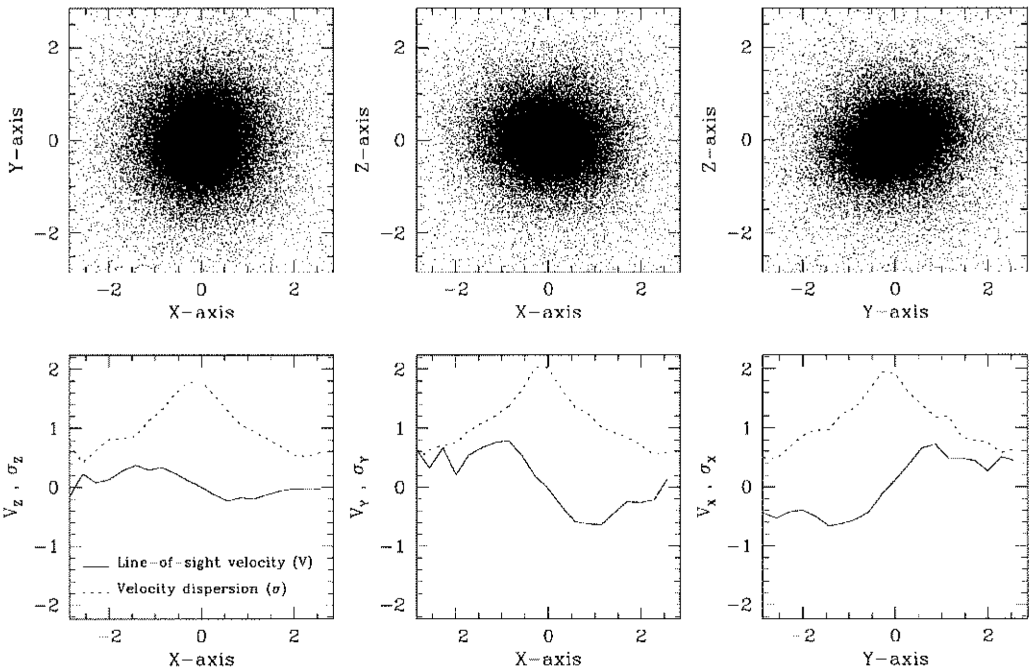

FIG. 2.—Final mass distributions (*top*) and kinematical properties (*bottom*), projected onto the x-y plane (*left*), the x-z plane (*middle*), and the y-z plane (*right*) in the fiducial model at $T = 32.0$ in our units (corresponding to 6.7×10^7 yr). Solid and dotted lines in each bottom panel represent the radial profile of line-of-sight velocity and that of the velocity dispersion, respectively. The length and the velocity are given in our units (34.0 pc and 15.9 km s^{-1}, respectively).

relation, it is possible that the relation is different over the range $-12 \leq M_V \leq -10$ mag and $-14 \leq M_V < -12$ mag (i.e., there is a hint of V-shaped distribution in Fig. 3).

Figure 4 shows the comparison between the locations of all of the simulated VMSCs in the M_V-σ_0 plane and the corresponding observations (Drinkwater et al. 2003). Here only five UCD points are plotted, since data for NCs are not available. The locations of the simulated brighter VMSCs are consistent with the observations, and both the simulated and the observed data points are closer to the Faber-Jackson relation than to the M_V-σ_0 relation of GCs (Djorgovski et al. 1997). This implies that the origin of UCDs' structural and kinematically properties is significantly different than that of GCs and is closely associated with the physics of multiple merging of SCs. Thus the present

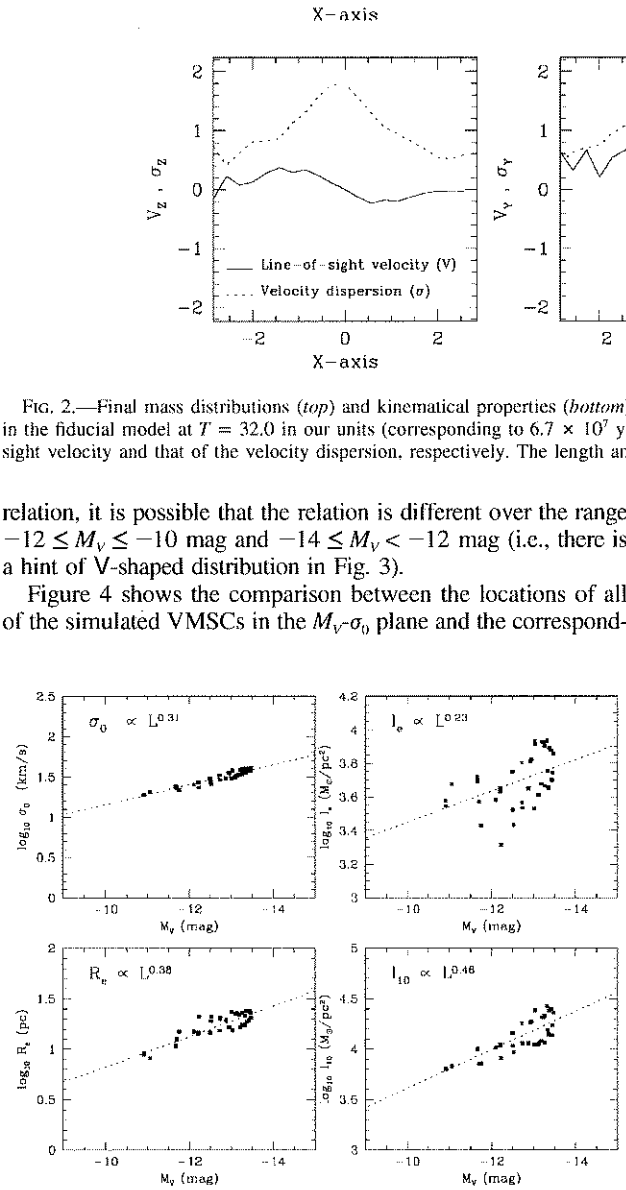

FIG. 3.—Correlations of structural and kinematical parameters with M_V (V-band absolute magnitude) for the VMSCs in 40 models including equal-mass two-dimensional and three-dimensional models with $C_V = 0$ and 0.5. Projected central velocity dispersion (σ_0; *top left*), half-light averaged surface brightness (I_e; *top right*), effective radius (R_e; *bottom left*), and central surface brightness (I_{10}; *bottom right*) are plotted against M_V. Here the central surface brightness I_{10} is expressed as $0.1L/\pi/R_{10}^2$, where L and R_{10} are the total luminosity of a VMSC and the radius within which 10% of L is included, respectively. The best-fit scaling relation for the VMSCs is derived for each panel using the least-square fitting method and described as a dotted line with the derived relation (e.g., $\sigma_0 \propto L^{0.31}$).

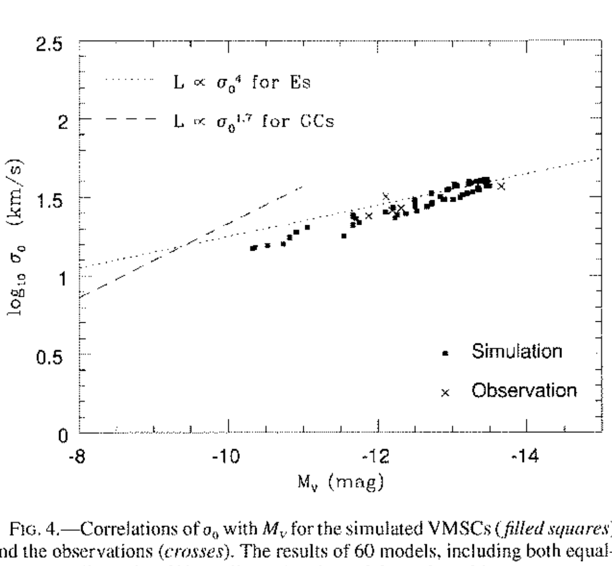

FIG. 4.—Correlations of σ_0 with M_V for the simulated VMSCs (*filled squares*) and the observations (*crosses*). The results of 60 models, including both equal-mass two-dimensional/three-dimensional models and multimass ones, are shown. Only five UCDs with known σ_0 (Drinkwater et al. 2003) are plotted (no velocity dispersion data for NCs are available). For comparison, the observed relations are given by a dashed line for GCs (Djorgovski et al. 1997) and a dotted line for elliptical galaxies (Faber & Jackson 1976).

results on the scaling relations of VMSCs clearly show that the scaling relations of VMSCs formed from multiple SC merging are significantly different both from those of their progenitor SCs (or GCs) and from those of dynamically hot early-type galaxies.

The parameter dependences of structural and kinematical properties of the simulated VMSCs can be summarized as follows: First, VMSCs are likely to be more flattened ($\epsilon = 0.2 \sim 0.3$) in the two-dimensional models than in the three-dimensional models for given parameter values of C_V and N_{SC}. Second, triaxial VMSCs in some two-dimensional models show large V_m/σ_0 ($\sim$0.4) and *figure rotation* such as barred galaxies. Third, the multimass three-dimensional models with large N_{SC} ($\geq$50) show both smaller ϵ (i.e., less flattened) and smaller V_m/σ_0 (i.e., less strongly supported by rotation). This is because a larger number of SCs merge with one another from random directions in the multimass three-dimensional models. These results suggest that the structural and kinematical properties of stellar galactic nuclei (i.e., NCs and UCDs) can differ, depending on the merging histories of SCs.

4. DISCUSSIONS AND CONCLUSIONS

We have demonstrated that if VMSCs are formed from the multiple merging of SCs, with the observed scaling relations of GCs, the scaling relations of VMSCs are very different from those of GCs. Ongoing and future photometric and spectroscopic observations (e.g., *HST* Advanced Camera for Surveys and Keck 10 m) of the structural and kinematical properties of VMSCs will therefore be able to assess the viability of the cluster cannibalism scenario of stellar nucleus formation.

We have also shown that (1) the intrinsic shapes of VMSCs are more likely to be triaxial, and (2) some VMSCs can have rotational kinematics. We thus suggest that further observations that provide better statistics on (1) the ϵ distributions of the projected isophotal shapes of VMSCs (which strongly depend on the intrinsic shapes of VMSCs) and (2) the locations of VMSCs on the $\epsilon - V_m/\sigma_0$ plane (which depend on the internal kinematics of VMSCs) will help discriminate between different VMSC formation scenarios.

Our study also has other important implications. First, the significant amount of rotation observed for the metal-poor populations in the most massive Galactic GC ω Cen (e.g., Norris et al. 1997) provides evidence that ω Cen may have originated from the nucleus of a dwarf galaxy. A growing number of observations and theoretical studies have recently suggested that ω Cen was previously a nucleus of an ancient nucleated dwarf orbiting the young Galaxy (e.g., Hilker & Richtler 2000, 2002; Bekki & Freeman 2003). The present study has demonstrated that VMSCs formed from SC merging can have a significant amount of rotation (i.e., larger V_m/σ_0) because of the conversion of orbital energy into intrinsic rotational energy. Therefore, the rotational kinematics of the metal-poor populations of ω Cen reflect the past merging of SCs *in the central region of its host galaxy*.

Second, we can significantly underestimate the mass-to-light ratios (*M/L*) of VMSCs, in particular those with large V_m/σ_0, if we estimate the *M/L* by adopting the commonly used formula in which *M/L* is derived only from the central velocity dispersion and effective radius (e.g., Meylan et al. 2001). This is simply because the implicit assumption (in the formula) that kinematical energy can be accurately measured by the central velocity dispersion σ_0 alone is not valid for these VMSCs. Accordingly, the real values of *M/L* for UCDs may be even larger than the moderately large values (*M/L* = 2–4) that are observed (Drinkwater et al. 2003), if UCDs indeed have rotational kinematics—something that future spectroscopic observations of UCDs can confirm.

Third, the observed young stellar populations in NCs (e.g., Böker et al. 2004b) can be due to nuclear star formation triggered by dynamical interaction between an NC and its surrounding interstellar gas. Recent numerical simulations have suggested that dynamical interaction between self-gravitating triaxial systems with figure rotation and the surrounding gas can cause rapid gas transfer to the central region and trigger subsequent starbursts there (Bekki & Freeman 2002). The present study has shown that some triaxial VMSCs have figure rotation (particularly when they are formed from SCs with initial disky distributions). Therefore, we suggest that the observed young populations in NCs may be due to past dynamical interaction between the triaxial NCs with figure rotation and the surrounding gas.

K. B. and W. J. C. acknowledge the financial support of the Australian Research Council throughout the course of this work.

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