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Kenji Bekki, Warrick J. Couch, Michael J. Drinkwater, Yasuhiro Shioya

Institutions: University of New South Wales, University of Queensland, Tohoku University

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CLUSTER CANNIBALISM AND SCALING RELATIONS OF GALACTIC STELLAR NUCLEI

KENJI BEKKI AND WARRICK J. COUCH
School of Physics, University of New South Wales, Kensington Campus, Old Main Building, Kensington, Sydney NSW 2052, Australia
MICHAEL J. DRINKWATER
Department of Physics, University of Queensland, Center for Laser Science, Queensland QLD 4072, Australia
AND
YASUHIRO SHIOYA
Astronomical Institute, Tohoku University, Aoba-ku, Sendai 980-8578, Japan
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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

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

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

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

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:

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

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.

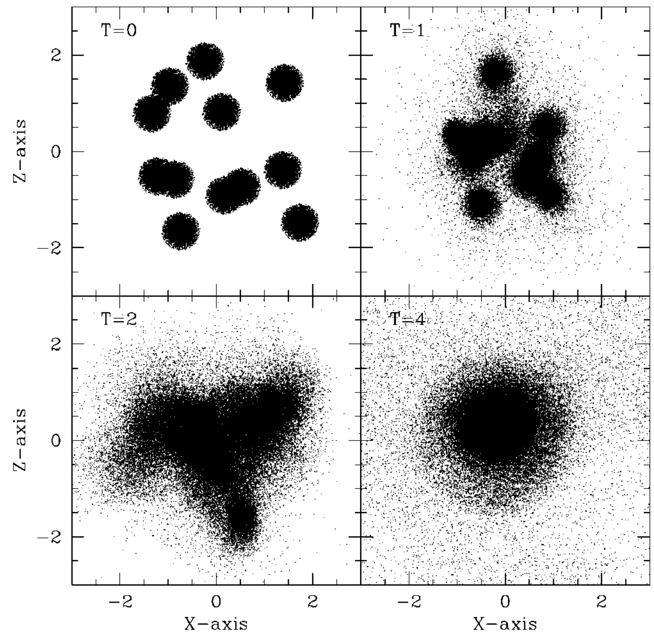

FIG. 1.—Morphological evolution of 12 equal-mass SCs projected onto the x-z plane for the fiducial model (with an initial total mass of $2.4 \times 10^7\ M_\odot$). The length and the time are given in our units (34.0 pc and 2.1×10^6 yr, respectively). Here the time T represents the time that has elapsed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

These bigger clusters then merge to form a single VMSC with an outer diffuse stellar envelope, within $\sim 10^7$ 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

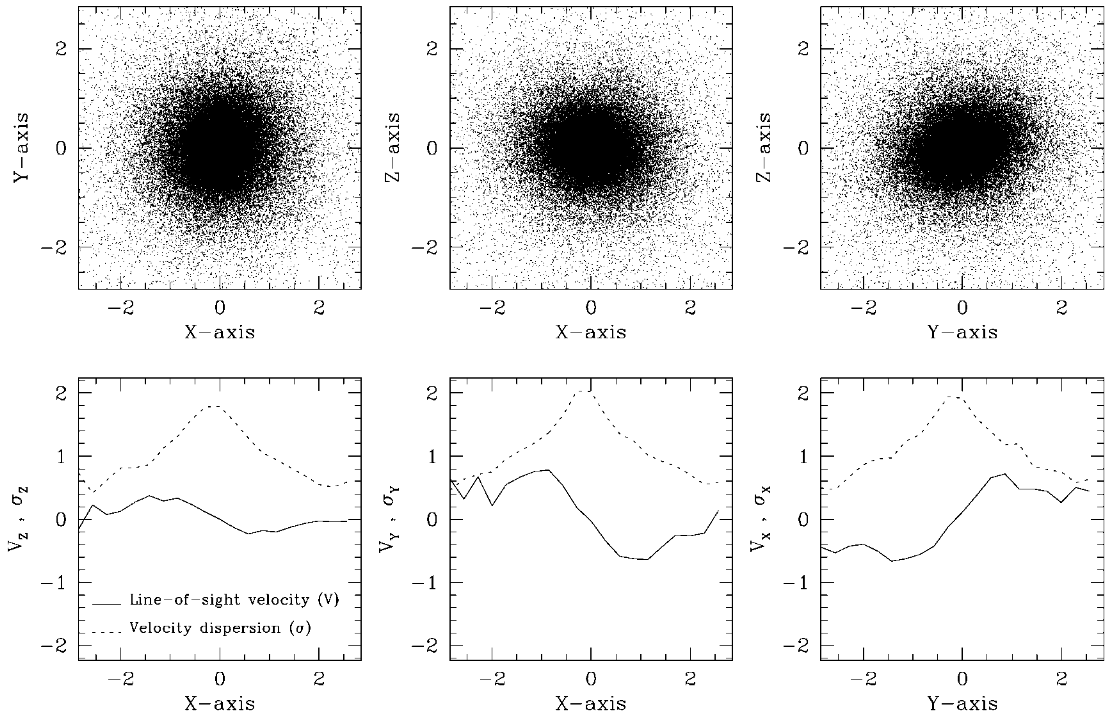

FIG. 2.—Final mass distributions (*top*) and kinematical properties (*bottom*), projected onto the *x-y* plane (*left*), the *x-z* plane (*middle*), and the *y-z* plane (*right*) in the fiducial model at $T = 32.0$ in our units (corresponding to 6.7×10^7 yr). Solid and dotted lines in each bottom panel 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

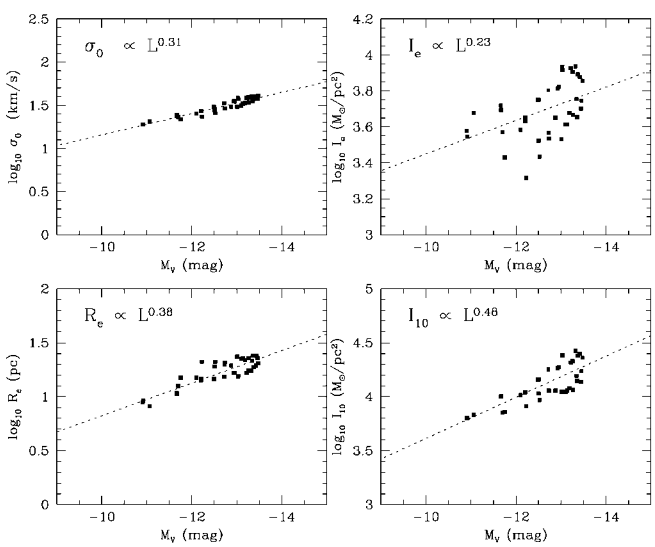

FIG. 3.—Correlations of structural and kinematical parameters with M_V (*V*-band absolute magnitude) for the VMSCs in 40 models including equal-mass two-dimensional and three-dimensional models with $C_V = 0$ and 0.5. Projected central velocity dispersion (σ_0; *top left*), half-light averaged surface 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., $\sigma_0 \propto L^{0.31}$).

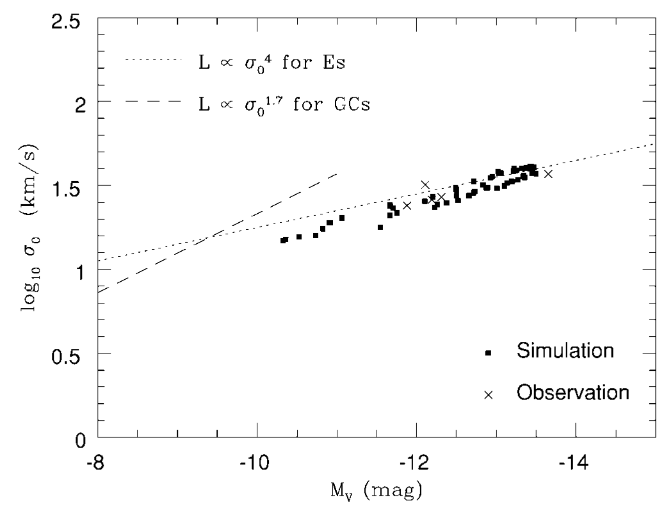

FIG. 4.—Correlations of σ_0 with M_V for the simulated VMSCs (*filled squares*) and the observations (*crosses*). The results of 60 models, including both equal-mass two-dimensional/three-dimensional models and multimass ones, are shown. Only five UCDs with known σ_0 (Drinkwater et al. 2003) are plotted (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 $N_{\rm SC}$. Second, triaxial VMSCs in some two-dimensional models show large V_m/σ_0 (~0.4) and *figure rotation* such as barred galaxies. Third, the multimass three-dimensional models with large $N_{\rm SC}$ (≥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.

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