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GALAXY THRESHING AND THE FORMATION OF ULTRACOMPACT DWARF GALAXIES

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ABSTRACT

Recent spectroscopic and morphological observational studies of galaxies around NGC 1399 in the Fornax Cluster have discovered several "ultracompact dwarf" galaxies with intrinsic sizes of ∼100 pc and absolute *B*-band magnitudes ranging from −13 to −11 mag. In order to elucidate the origin of these enigmatic objects, we perform numerical simulations on the dynamical evolution of nucleated dwarf galaxies orbiting NGC 1399 and suffering from its strong tidal gravitational field. Adopting a plausible scaling relation for dwarf galaxies, we find that the outer stellar components of a nucleated dwarf are totally removed. This is due to them being tidally stripped over the course of several passages past the central region of NGC 1399. The nucleus, however, manages to survive. We also find that the size and luminosity of the remnant are similar to those observed for ultracompact dwarf galaxies, if the simulated precursor nucleated dwarf has a mass of $\sim 10^8\ M_\odot$. These results suggest that ultracompact dwarf galaxies could have previously been more luminous dwarf spheroidal or elliptical galaxies with rather compact nuclei.

Subject headings: galaxies: clusters: general — galaxies: dwarf — galaxies: elliptical and lenticular, cD — galaxies: formation — galaxies: interactions

1. INTRODUCTION

Strong constraints on theoretical models of galaxy formation and evolution have been provided by observational studies of the physical properties of low-luminosity and low surface brightness dwarf spheroidal and irregular galaxies in the field and in clusters (e.g., Ferguson & Binggeli 1994; Mateo 1998). In detail, these studies have addressed such observables as the scaling relation (Kormendy 1977; Ferguson & Binggeli 1994), the luminosity function (Binggeli, Sandage, & Tammann 1985; Sandage, Binggeli, & Tammann 1985), the presence of nuclear structures (Binggeli & Cameron 1991), and rotation-curve profiles (Moore 1994). 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, 2001). These have already been identified as bright compact objects (Hilker, Infante, & Richtler 1999) and very luminous globular clusters around cD galaxies (Harris, Pritchet, & McClure 1995). These "dwarf galaxies," which are members of the Fornax Cluster, have intrinsic sizes of ∼100 pc and absolute *B*-band magnitudes ranging from −13 to −11 mag and are thus called "ultracompact dwarf" (UCD) galaxies. The luminosities of UCDs are intermediate between those of globular clusters and small dwarf galaxies and are similar to those of the bright end of the luminosity function of the nuclei of nucleated dwarf elliptical galaxies. These UCDs are observed to be within 30′ of the central dominant galaxy in Fornax, NGC 1399, and are distributed at larger radii than this galaxy's globular cluster system.

The purpose of this Letter is to suggest one possible origin for these newly discovered enigmatic UCDs. We adopt here the scenario that UCDs are the stripped nuclei of dwarf galaxies and thereby investigate numerically how nucleated dwarf spheroidal galaxies evolve dynamically under the strong tidal field of NGC 1399. A growing number of evidence supporting this scenario has been accumulating for the case of ω Cen and M54 (e.g., Majewski et al. 2000; Layden & Sarajedini 2000; van den Bergh 2000). We here demonstrate (1) how a UCD is formed when a nucleated dwarf galaxy is subjected to the strong tidal field of a massive galaxy such as NGC 1399 and (2) in what physical conditions this process of nucleated dwarf galaxy to UCD formation can take place. The importance of the tidal field of more massive galaxies in forming globular clusters (and even objects that are an order of magnitude brighter than globular clusters) from nucleated dwarf galaxies has already been discussed by several authors (e.g., Zinnecker et al. 1988; Freeman 1993; Bassino, Muzzio, & Rabolli 1994). Extraction of *only* galactic nuclei from less massive galaxies by the tidal effects of more massive ones is suggested to be important in a variety of different contexts, such as the evolution of M32 and the formation of Galactic halo globular clusters (K. Bekki, W. J. Couch, & M. J. Drinkwater 2001, in preparation). We can think of and refer to this tidal effect as "galaxy threshing."

2. MODEL

We consider a collisionless stellar system with a mass and size similar to that of nucleated dwarf galaxies, orbiting a massive elliptical galaxy (e.g., NGC 1399) that is embedded within a massive dark matter halo. To give our model a realistic radial density profile for the NGC 1399 dark matter halo, we base it on both the X-ray observational results of Jones et al. (1997) and the predictions from the standard cold dark matter cosmogony (Navarro, Frenk, & White 1996). The total mass of NGC 1399 within 125 kpc (represented by M_E) and the scale length of the halo are assumed to be $8.1 \times 10^{12}\ M_\odot$ and 43.5 kpc, respectively. By using two Plummer models (Binney & Tremaine 1987) with rather different scale lengths, we construct a model for nucleated dwarf galaxies as follows: First, we place a smaller spherical stellar system having a Plummer density profile with scale length a_n and mass M_n in the center of a larger spherical system with a Plummer profile of scale length a_d and mass M_d ($a_d \gg a_n$ and $M_d \gg M_n$). Second, in order to get the model to reach a new dynamical equilibrium, we run the simulation of

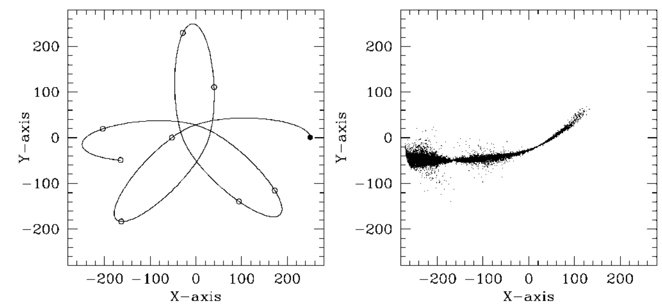

FIG. 1.—*Left*: Orbital evolution of the simulated dwarf with respect to the center of NGC 1399. *Right*: Final mass distribution of the dwarf at $T = 160$ in our units. The center of NGC 1399 is set to be always $(x, y) = (0, 0)$. Here the scale is given in our units (0.8 kpc), and thus each frame measures 448 kpc. The filled circle represents the position of the dwarf at $T = 0$, and the orbital evolution is indicated by open circles with the time interval of 20 time units corresponding to 4.7×10^8 yr (T = 0, 20, 40, 60, 80, 100, 120, 140, and 160). Note that owing to the strong tidal field of NGC 1399, the dwarf is greatly stretched, and most of the outer stellar components of the dwarf are tidally stripped away from it at $T = 160$ (3.8 Gyr).

the dynamical evolution in the nested Plummer models for 10 dynamical timescales. Finally, we use the stellar system as the model for a nucleated dwarf galaxy. From now on, the outer (more massive) diffuse stellar component and the inner (less massive) compact one are referred to as the "envelope" and "nucleus," respectively.

The mass (luminosity) and the scale length of a dwarf are modeled according to the observed scaling relation of Ferguson & Binggeli (1994): $\log r_0\,[\mathrm{pc}] = -0.2M_B - 0.3$ for bright dwarfs ($M_B < -16$) and $\log r_0\,[\mathrm{pc}] = -0.02M_B + 2.6$ for faint ones ($M_B \geq -16$), where r_0 and M_B are the scale length of the exponential profile and B-band absolute magnitude, respectively. By assuming that $a_d = r_0$ and M/L_B (the ratio of total stellar mass to total B-band luminosity) = 1.0, corresponding to the observed value of the dwarf galaxy DDO 154 (Carignan & Beaulieu 1989), we determine a_d from the total mass ($= M_d + M_n$) of the model. Since the nuclei typically contributes about 2% of the total light of dwarfs (Binggeli & Cameron 1991; Freeman 1993), we assume that $M_n/(M_d + M_n) = 0.02$ for all models. Considering the fact that the central light excess with respect to the adopted model profile is observed to vary between nucleated dwarfs (e.g., Binggeli & Cameron 1991; Ferguson & Binggeli 1994), we take the scale length ratio a_n/a_d of the nested Plummer models to be a free parameter. We investigate nucleated dwarf models in the luminosity range $-18 \leq M_B \leq -12$ and with a_n/a_d ranging from 0.05 to 0.5.

The orbit of a nucleated dwarf is assumed to be influenced only by the gravitational potential resulting from the dark halo component of NGC 1399. The center of NGC 1399 is always set to be $(x, y) = (0, 0)$, whereas the initial position and velocity of a dwarf are $(x, y) = (r_{\mathrm{in}}, 0)$ and $(V_x, V_y) = (0, V_{\mathrm{in}})$, respectively. By changing these two parameters r_{in} and V_{in}, we investigate how the transformation process from dwarfs into UCDs depends on their orbits. Although we have investigated models with a variety of different M_d-, a_d-, r_{in}-, and V_{in}-values, we mainly describe here the results of a "standard" model with a total mass of $M_d + M_n = 2.0 \times 10^8\ M_\odot$, $a_d = 7.94 \times 10^2$ pc, $a_n = 79.4$ pc, $r_{\mathrm{in}} = 200$ kpc, and $V_{\mathrm{in}} = 1.29 \times 10^2$ km s^{-1}. Figure 1 shows the orbit with respect to NGC 1399 and the final mass distribution for the simulated dwarf galaxy in the standard model.

In the following, our units of mass, length, and time are $2.0 \times 10^8\ M_\odot$ (corresponding to $M_d + M_n$ in the standard model), 7.94×10^2 pc (a_d), and 2.36×10^7 yr (dynamical timescale), respectively. Parameter values and final morphologies for each model are summarized in Table 1. The sixth and the seventh columns give the orbital eccentricity (e) and pericenter distance (r_p), respectively, for each model. The eighth column describes the final morphological properties after 160 time units (corresponding to 3.8 Gyr): "UCD" indicates a remnant with the envelope completely stripped yet the nucleus largely unaffected, "*dE, N*" the case in which both the envelope and nucleus survive, and "No remnant" the case in which both components are tidally stripped. All the simulations have been carried out on a GRAPE board (Sugimoto et al. 1990) in which energy and angular momentum are conserved within 1% accuracy. The total number of particles used for each model and the gravitational softening length adopted for its envelope (nucleus) were 10,000 (5000) and 0.47 (0.06) in our units, respectively.

3. RESULTS

As the dwarf approaches the pericenter of its orbit for the first time ($T = 20$), the strong tidal field of NGC 1399 stretches the envelope along the direction of the dwarf's orbit and consequently tidally strips the stars of the envelope (see Fig. 2). Since the envelope loses a significant fraction of its mass after the first passage of the pericenter, the envelope becomes more susceptible to the tidal effects of NGC 1399. As the dwarf again approaches the pericenter ($T \sim 50$ and 90), the envelope again loses a large number of its stars owing to tidal stripping and consequently becomes less massive and more diffuse. After four passages of the pericenter, the dwarf loses its envelope almost entirely. The central nucleus, on the other hand, is just weakly influenced by the tidal force owing to its compact configuration during the tidal destruction of the envelope. Thanks to its strongly self-gravitating nature, the nucleus loses only a

TABLE 1
RESULTS OF DIFFERENT MODELS OF TIDAL INTERACTION BETWEEN A *dE, N* AND A GIANT GALAXY

Model	M_E ($\times 10^{13}\ M_\odot$)	M_d ($\times 10^8\ M_\odot$)	a_n/a_d	r_{in} (kpc)	e	r_p (kpc)	Final Morphology
1 ……	8.1	2.0	0.1	200	0.81	21	UCD
2 ……	8.1	2.0	0.5	200	0.81	21	No remnant
3 ……	8.1	2.0	0.1	200	0.35	95	*dE, N*
4 ……	8.1	2.0	0.1	80	0.34	39	UCD
5 ……	8.1	0.05	0.1	200	0.81	21	UCD
6 ……	8.1	0.31	0.1	200	0.81	21	UCD
7 ……	8.1	12.2	0.1	200	0.81	21	UCD
8 ……	0.8	2.0	0.1	200	0.81	21	*dE, N*

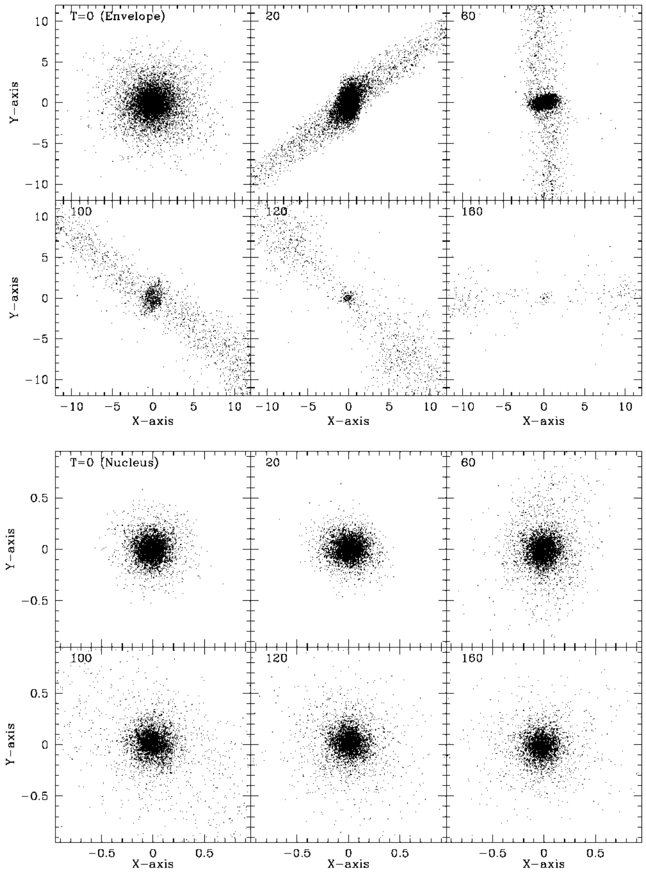

FIG. 2.—Morphological evolution projected onto the *x-y* plane for the envelope (*upper six panels*) and the nucleus (*lower six panels*) in the simulated dwarf. The detailed explanation for the definition of the envelope and the nucleus is given in the text. The time indicated in the upper left-hand corner of each frame is given in our units (2.36×10^7 yr), and each frame measures 19.2 kpc for the upper six (envelope) and 1.52 kpc for the lower six (nucleus). Note that nearly all of the stars initially in the envelope of the dwarf are tidally stripped away, whereas the nucleus keeps its initial compact configuration. This result clearly demonstrates that the strong tidal field of a giant galaxy can transform a nucleated dwarf into a very compact galaxy.

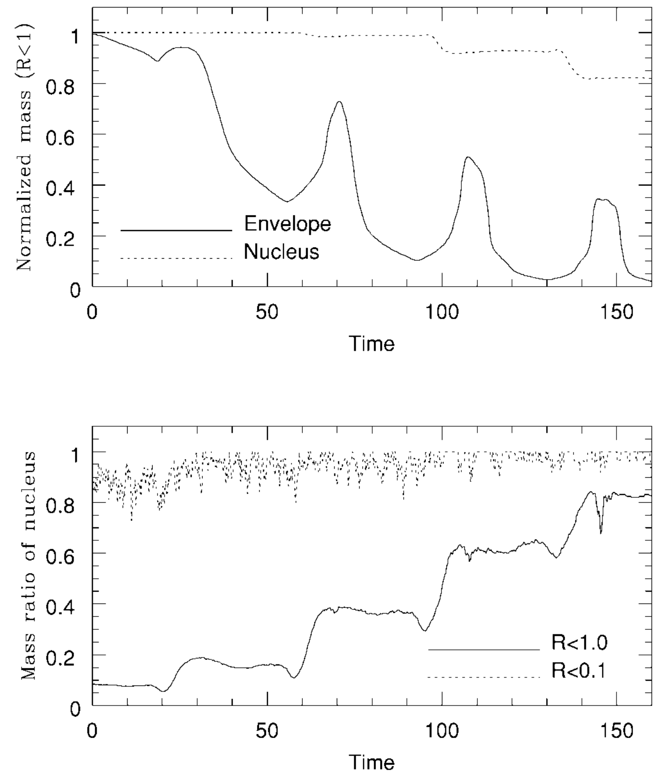

FIG. 3.—*Top*: Time evolution of the total mass within $R < 1$ ($=a_d$) in our units, where R is the distance from the center of the dwarf, for the envelope (*solid line*) and the nucleus (*dotted line*). Here the mass normalized by the initial mass ($T = 0$) within $R < 1$ is plotted for both the envelope and the nucleus. Therefore, the solid (dotted) line describes what fraction of stars initially in the envelope (nucleus) is removed from the system at each time. Note that the envelope's stars are preferentially stripped during tidal interaction between NGC 1399 and the dwarf. Note also that although only ∼7.5% of the stars in the nucleus are tidally stripped at $T = 160$, nearly all (∼98%) of the stars in the envelope are stripped. *Bottom*: Time evolution of the ratio of nucleus mass (M_n) to total mass ($M_d + M_n$) for $R < 1.0$ (*solid line*) and $R < 0.1$ (*dotted line*). This figure describes how strongly the nucleus becomes self-gravitating at each time. It is clear that as the envelope is gradually removed, the nucleus becomes more strongly self-gravitating not only in the inner part ($R < 0.1$) but also in the outer one ($R < 1$).

small amount (∼18%) of mass and thus can keep its compact morphology during its tidal interaction with NGC 1399.

Figure 3 shows that a significant fraction of the envelope of the dwarf is tidally stripped every time it passes through the inner part of NGC 1399 (e.g., 63% between $T = 25$ and 60). As a result of this, nearly all (98%) of the stars within the dwarf's envelope (radius $<a_d$ [$=0.8$ kpc]) are removed within four passages of its pericenter (corresponding to 3.8×10^9 yr). The temporal increase of the envelope mass within a_d around the apocenter is due to the fact that a significant fraction of stripped stars pass through the surrounds of the dwarf. The ratio of the nuclear mass to the total mass is dramatically changed from 0.08 (0.85) to 0.83 (1.0) for $R \leq a_d$ ($R \leq 0.1a_d$), which implies that the final remnant after "threshing" is nearly fully self-gravitating. Thus, a UCD of size ∼100 pc and mass 4.0×10^6 $M_{\odot}$ (corresponding to $M_B = -12.4$ mag for $M/L_B = 1.0$) is formed from the tidal interaction between a nucleated dwarf and NGC 1399. It is clear from Figures 2 and 3 that before the formation of a UCD is completed, a compact nucleus with a considerably diffuse outer envelope is seen (e.g., $T = 100$). This suggests the existence of extremely diffuse nucleated dwarf galaxies, formed in this intermediate stage of the *dE, N* → UCD conversion process. As is shown in Figure 4, the remnant shows a rather compact density distribution because of it being composed mostly of the self-gravitating nucleus at $T = 160$.

Four important parameter dependences in the formation of UCDs were found as follows (see the Table 1): For the model in which the nucleus of the dwarf is not so compact ($a_n/a_d \sim 0.5$; model 2), both the nuclear and envelope components disintegrate under the influence of the tidal field, and, accordingly, no remnant is left. A UCD is not formed in model 3 with larger values of $r_{\rm in}$ (200 kpc) and r_p (95 kpc) but with a smaller ellipticity ($e = 0.35$), whereas one is in model 4 with a smaller $r_{\rm in}$ (100 kpc) and a smaller e (0.34). This suggests that nucleated dwarfs with either a smaller r_p (or smaller e) or a smaller $r_{\rm in}$ are more likely to be transformed into a UCD, and thus UCDs should show a centrally concentrated spatial distribution around NGC 1399. Third, the formation of a UCD seems to have no dependence on the mass of the nucleated dwarf's envelope, M_d, as shown by models 1, 5, 6, and 7. Irrespective of the masses of these models with $e = 0.81$ and $r_p = 21$ kpc, UCDs are formed by galaxy threshing. This indicates that UCDs ob-

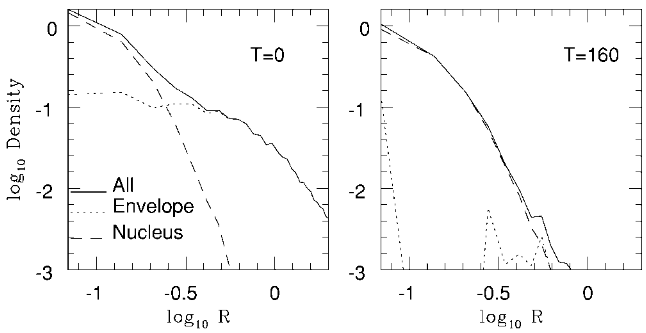

FIG. 4.—Density profiles of the simulated dwarf at $T = 0$ (*left*) and 160 (*right*). The profiles for all, the envelope, and the nucleus components are given by solid, dotted, and dashed lines, respectively. Note that the nucleus component dominates almost exclusively the final density profile of the simulated dwarf.

served to have different masses were previously the nuclei of nucleated dwarfs with different masses. Finally, for the model with a rather small mass for NGC 1399 (model 8), disintegration of the simulated nucleated dwarf does not occur at all, even if r_p is small. This suggests that UCDs are formed only in the surrounds of massive galaxies.

Several observational properties of nucleated dwarf galaxies (e.g., Freeman 1993) and numerical simulations (Bassino et al. 1994) suggest that globular clusters are the stripped nuclei of dwarf galaxies. We have confirmed the "disintegration scenario" (Bassino et al. 1994) in which UCDs (-13 mag $\leq M_B \leq -11$ mag), which are more than an order of magnitude brighter than the Galactic globular clusters, were also previously nuclei of more massive dwarf galaxies ($M_d \sim 10^8\ M_\odot$) orbiting NGC 1399. Accordingly, it is likely that physical properties of UCDs such as the luminosity-size relation and stellar content are more like those of globular clusters than those of dwarf spheroidal/elliptical galaxies: it might not be correct to call the observed compact objects around NGC 1399 "dwarf galaxies." Our numerical simulations with variously different parameters revealed that not all of nucleated dwarfs can be transformed into UCDs by galaxy threshing (e.g., for the case of the smaller ratio of the dwarf mass to the giant mass), which suggests that the number ratio of UCDs to nucleated dwarfs is different between different environments.

4. CONCLUSION

The present study provides the following two implications as to the nature of UCDs. First, the stellar populations of UCDs are unlikely to be young even if the precursor nuclei of dwarf galaxies have obviously young populations. This is essentially because more than a few gigayears, which is enough for young stars to become intermediate-age populations due to aging, are necessary for galaxy threshing to transform a nucleated dwarf into a UCD. Second, the UCD luminosity function is not necessarily similar to that of the nuclei of nucleated dwarf galaxies because galaxy threshing is a selective process: extraction of the nucleus depends strongly on the orbits and masses of the dwarfs. Since these physical properties can be directly observed in future observations—not only in the Fornax Cluster but also in other nearby clusters such as Coma and Virgo—they will provide a critical test of the viability of the threshing scenario for UCD formation.

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