A NEW FORMATION MODEL FOR M32: A THRESHED EARLY-TYPE SPIRAL GALAXY?

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ABSTRACT

The origin of M32, the closest compact elliptical galaxy (cE), is a long-standing puzzle of galaxy formation in the Local Group. Our *N*-body/smoothed particle hydrodynamics simulations suggest a new scenario in which the strong tidal field of M31 can transform a spiral galaxy into a compact elliptical galaxy. As a low-luminosity spiral galaxy plunges into the central region of M31, most of the outer stellar and gaseous components of its disk are dramatically stripped as a result of M31's tidal field. The central bulge component, on the other hand, is just weakly influenced by the tidal field, owing to its compact configuration, and retains its morphology. M31's strong tidal field also induces rapid gas transfer to the central region, triggers a nuclear starburst, and consequently forms the central high-density and more metal-rich stellar populations with relatively young ages. Thus, in this scenario, M32 was previously the bulge of a spiral galaxy tidally interacting with M31 several gigayears ago. Furthermore, we suggest that cE's like M32 are rare, the result of both the rather narrow parameter space for tidal interactions that morphologically transform spiral galaxies into cE's and the very short timescale (less than a few times 10^9 yr) for cE's to be swallowed by their giant host galaxies (via dynamical friction) after their formation.

Subject headings: galaxies: bulges — galaxies: elliptical and lenticular, cD — galaxies: formation — galaxies: interactions

1. INTRODUCTION

Andromeda's (M31) closest companion, M32, has long served as a laboratory that can provide valuable information not only on the nature of stellar populations of low-mass elliptical galaxies but also on the detailed structure of their nuclei (e.g., Davidge 2000; van den Bergh 2000). M32 is classified, morphologically, as a compact elliptical galaxy (cE) that has a rather high central surface brightness (~4 orders of magnitude higher than that of typical spheroidals of comparable total luminosity), a truncated de Vaucouleurs profile, and solar-like metallicity (e.g., Kormendy 1985; Nieto & Prugniel 1987). M32-like cE's are observed to be located almost exclusively in the vicinity of bright galaxies (Nieto & Prugniel 1987) and generally considered to be very rare objects both in the field and in clusters (Kormendy 1985; Ziegler & Bender 1998; Drinkwater & Gregg 1998). A large number of previous spectroscopic studies aimed at placing strong constraints on M32's star formation history have suggested the existence of young stellar populations with ages of several gigayears (e.g., O'Connell 1980; Burstein et al. 1984; Rose 1985; Bica, Alloin, & Schmidt 1990; Vazdekis & Arimoto 1999; del Burgo et al. 2001), although recent studies have argued that there is no clear evidence supporting M32's relatively recent star formation (e.g., Cole et al. 1998; Renzini 1998). The most recent spectroscopic studies have suggested that M32 has relatively young (approximately several gigayears old) stellar populations (e.g., del Burgo et al. 2001; Davidge et al. 2000; see Davidge 2000 and van den Bergh 2000 for a recent review).

The origin of the high surface brightness of cE's and radially limited luminosity profiles has been discussed mostly in the context of the tidal effects of massive galaxies close to them (King 1962; Faber 1973; Nieto & Prugniel 1987; Burkert 1994). For example, Faber (1973) first proposed that M32 was pre-

viously the inner high-density region of a low-luminosity elliptical galaxy with the outer part stripped by M31's tidal field. Burkert (1994) proposed an alternative scenario that M32 formed through starbursts and the subsequent violent gravitational collapse in M31's vicinity, where its strong tidal field can induce very efficient violent relaxation in the M32 collapse. However, it is still controversial how these models can provide a plausible explanation for the observationally suggested intermediate-age (~5 Gyr) stellar populations in M32.

Through numerical simulations, we have investigated how M31's strong tidal field affects the chemical and dynamical evolution of a gas-rich spiral galaxy plunging into the central region of M31, demonstrating that dissipative tidal interactions can dramatically transform a spiral galaxy into a cE galaxy such as M32. In this scenario, a gas-rich disk galaxy with a compact bulge, captured by M31 several gigayears ago, loses a significant fraction of its initial disk mass during dynamical interaction with M31 through tidal stripping. The central bulge component, on the other hand, survives, retaining its compactness.

Although this "threshed spiral" (for the concept of galaxy "threshing," see Bekki, Couch, & Drinkwater 2001, hereafter BCD) scenario has already been speculated on by several authors (e.g., Nieto 1990; van den Bergh 2000), the present numerical study is the first to demonstrate that this scenario is realistic and viable for the formation of M32. This scenario is in striking contrast to the canonical one (Wirth & Gallagher 1984; Kormendy 1985), in which cE's like M32 form the faint branch of the normal elliptical sequence.

2. MODEL

We consider a gas-rich disk galaxy with a bulge, orbiting a massive disk galaxy with structural and kinematical properties similar to those of M31. We adopt the TREESPH codes described
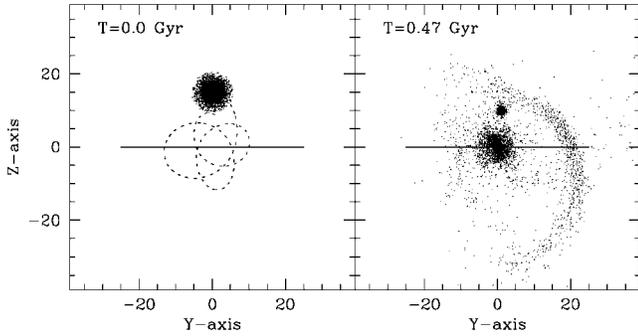
FIG. 1.—Initial (*left*) and final (*right*) mass distribution of the simulated spiral galaxy projected onto the y-z plane (face-on) for the standard model. The orbital evolution of the spiral galaxy with respect to the center of M31 is also given by the dashed line in the left panel in order that the dynamical evolution can be seen more clearly. The center of M31 is set to be always $(x, y, z) = (0, 0, 0)$, and the initial and final positions of the spiral galaxy are $(x, y, z) = (1.3, 0, 15.0)$ and $(1.0, 1.3, 8.5)$, respectively. The scale is given in our units (0.8 kpc), and thus each frame measures 62 kpc on a side. The initial position and size of M31's disk are given by a solid line for each panel. Note that owing to the strong tidal field of M31, a significant fraction of the outer stellar disk of the spiral galaxy (both old and young stars) is stripped away at $T = 0.47$ Gyr: only a compact bulge can be seen at $(x, y, z) = (1.0, 1.3, 8.5)$ [The apparently high surface density clumping of stars around $(x, y, z) = (0, 0, 0)$ is due to the tidal debris of the spiral galaxy.] Note also that without including the effects of dynamical friction in the model, the apocenter distance of the orbit becomes smaller owing to the mass loss of the spiral galaxy preferentially at its pericenter. The surface brightness of the tidal debris is estimated to be ~26 mag arcsec^{-2} in the V band for the M32's distance of 760 kpc from the Galaxy.

in Bekki (1995) for the hydrodynamical evolution of galaxies. We use the disk model of Fall & Efstathiou (1980) with a dark halo–to–disk mass ratio equal to 4 for M32's progenitor disk. The total mass (M_d) and the size of the exponential disk (R_d) are $4.0 \times 10^9\ M_\odot$ and 4.5 kpc (scale length of 0.9 kpc), respectively. The gas mass fraction is set to be 0.1, and an isothermal equation of state is used for the gas with a temperature of 7.3×10^3 K, corresponding to a sound speed of 10 km s^{-1}. Star formation is modeled according to the Schmidt law (Schmidt 1959) with an exponent of 1.5. The central bulge is modeled by the Plummer model (Binney & Tremaine 1987) with total mass of $2.0 \times 10^9\ M_\odot$, corresponding to a bulge mass fraction of 0.33 and scale length of 0.25 kpc. The total number of particles used for each model is 20,000 for collisionless particles and 5000 for gaseous ones.

The orbit of the spiral galaxy is assumed to be influenced only by the *fixed* gravitational potential of M31, having three components: a dark matter halo, a disk, and a bulge. We assume a logarithmic dark matter halo potential,

$$\Phi_{\mathrm{halo}} = v_{\mathrm{halo}}^2 \ln (r^2 + d^2), \qquad (1)$$

a Miyamoto & Nagai (1975) disk,

$$\Phi_{\mathrm{disk}} = -\frac{GM_{\mathrm{disk}}}{\sqrt{R^2 + (a + \sqrt{z^2 + b^2})^2}}, \qquad (2)$$

and a spherical Hernquist (1990) bulge,

$$\Phi_{\mathrm{bulge}} = -\frac{GM_{\mathrm{bulge}}}{r + c}, \qquad (3)$$

TABLE 1
RESULTS OF DIFFERENT MODELS OF TIDAL INTERACTION BETWEEN A SPIRAL GALAXY AND M31

Model	r_{in} (kpc)	V_{in} (km s^{-1})	r_p (kpc)	Final Morphology	Comments
1	12	142	4.5	cE	Standard model
2	...	...	...	Sa	Isolated model
3	12	28	0.5	No remnant	
4	12	212	8.8	cE	
5	12	255	10.7	S0	
6	24	50	2.2	cE	
7	24	188	15.0	S0	
8	24	376	24.0	Sa	Circular orbit

where r is the distance from the center of M31, $d = 12$ kpc, $v_{\mathrm{halo}} = 131.5$ km s^{-1}, $M_{\mathrm{disk}} = 1.3 \times 10^{11}\ M_\odot$, $a = 6.5$ kpc, $b = 0.26$ kpc, $M_{\mathrm{bulge}} = 9.2 \times 10^{10}\ M_\odot$, and $c = 0.7$ kpc. This reasonable set of parameters gives a realistic rotation curve for M31 with a rotation speed of 260 km s^{-1} at 26 kpc.

The center of M31 is always set to be $(x, y, z) = (0, 0, 0)$, whereas the initial position and velocity of the spiral galaxy are $(x, y, z) = (0, 0, r_{\mathrm{in}})$ and $(V_x, V_y, V_z) = (0, V_{\mathrm{in}}, 0)$, respectively. By changing these two parameters r_{in} and V_{in}, we investigate how the transformation process from spiral galaxies into cE's depends on their orbits. Although we have investigated models with a variety of different r_{in} and V_{in}, we mainly describe here the results of a "standard" model with $r_{\mathrm{in}} = 12$ kpc and $V_{\mathrm{in}} = 142$ km s^{-1} (corresponding to $0.5V_c$, where V_c is a circular velocity of M31 at this radius). Figure 1 shows the orbit with respect to M31 and the final mass distribution for the simulated M32 in the standard model. We choose this nearly polar orbit from the most likely M32 orbit by Cepa & Beckman (1988).

In the following, our units of mass, length, and time are $2.0 \times 10^8\ M_\odot$, 7.94×10^2 pc, and 2.36×10^7 yr, respectively. The parameter values and final morphologies for each model are summarized in Table 1. The fourth column gives the pericenter distance (r_p) for each model. The fifth column describes the final morphological properties after 32 time units (corresponding to 0.76 Gyr): "cE" indicates a remnant with the outer disk completely stripped yet with the bulge largely unaffected, "S0" indicates the case in which both the outer disk and the bulge survive yet the disk is partly stripped (thus becoming a smaller disk) and rather thickened owing to dynamical heating, "no remnant" the case in which both disk and bulge components are tidally destroyed, and "Sa" the case in which the spiral galaxy keeps its initial morphology.

3. RESULTS

As the spiral galaxy approaches the pericenter of its orbit for the first time ($T = 0.09$ Gyr), the strong tidal field of M31 stretches the stellar disk along the direction of the spiral galaxy's orbit and consequently tidally strips the stars of the disk (see Fig. 2). The disk gradually loses a large number of its stars from its outer part (0.09 Gyr $< T < 0.38$ Gyr) and finally loses most of its outer stellar disk ($T = 0.47$ Gyr): the spiral galaxy can keep only stars initially in the central region where the bulge gravitational field dominates. Although galaxy-scale star formation is triggered by the tidal interaction, the outer new stellar component is also tidally stripped away from the spiral galaxy, and consequently only the central starburst component survives. The central bulge, on the other hand, is just weakly influenced by the tidal force because of its compact configuration during the tidal destruction of the outer spiral galaxy.
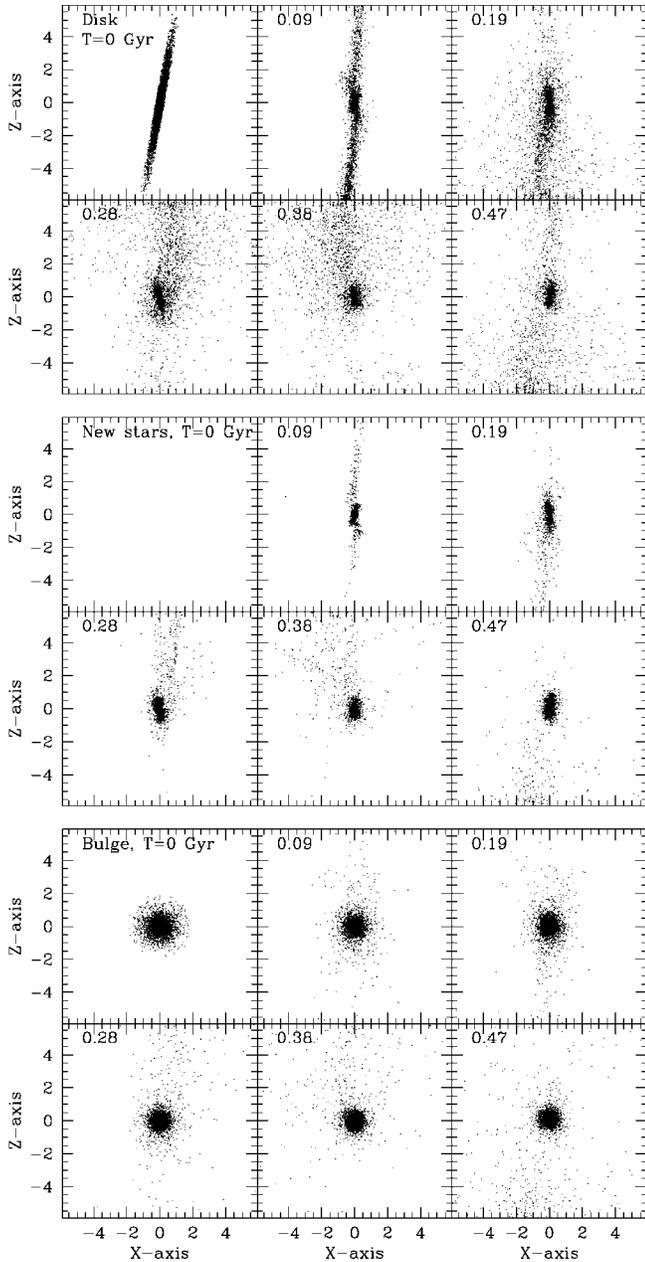
FIG. 2.—Morphological evolution projected onto the *x-z* plane (edge-on) for the stellar disk (*top six panels*), the new stars formed from gas (*middle six panels*), and the bulge (*bottom six panels*) in the simulated spiral galaxy. The time indicated in the upper left-hand corner of each frame is given in gigayears, and each frame measures 9.4 kpc on a side.

FIG. 3.—*Left*: Time evolution of normalized mass within the central 5 kpc (corresponding to the disk size of the spiral galaxy) for the stellar disk (*solid line*), the new stars formed from gas (*dotted line*), and the bulge (*dashed line*) in the simulated spiral galaxy. Here the mass of the stellar disk and that of the bulge are normalized by their initial masses, whereas that of the new stars is normalized by its maximum mass within 5 kpc. *Right*: Time evolution of fractional mass within the central 2 kpc (correspondingly, ~2 times larger than the initial size of the bulge) for the stellar disk (*solid line*), the new stars (*dotted line*), and the bulge (*dashed line*).

greatly increases to reach 0.08, which implies that the simulated M32 can have a remarkable fraction of young stars for an elliptical galaxy.

The tidal distortion forms nonaxisymmetric structures (spiral galaxies and bars) and induces efficient gaseous dissipation in the shocked gaseous region, with the subsequent rapid radial gas transfer to the central region, which consequently triggers a massive starburst (see Fig. 4). This starburst trigger mechanism is essentially the same as that already demonstrated by Noguchi & Ishibashi (1986) for the case of a galaxy-galaxy interaction. The maximum star formation rate is 9.5 $M_\odot$ yr^{-1} (at $T = 0.07$ Gyr), which is correspondingly ~31 times higher than the mean star formation rate of the isolated disk model (0.31 $M_\odot$ yr^{-1}). Owing to this starburst, a significant fraction of gas (64%, which is correspondingly 2.2 times larger than the isolated model case) is consumed by the star formation, and most of the remaining gas is tidally stripped away from the disk. Owing to chemical evolution associated with this efficient star formation, the bulge finally has a young stellar population with a mean metallicity of [Fe/H] = 0.1 and a radial metallicity gradient. The central, more metal-rich components and the gradient may well be responsible for M32 being observed to have stronger CN and Mg absorption for its luminosity (Faber 1973) and partly associated with the origin of the radial variations of total asymptotic giant branch luminosity observed in M32 (Davidge et al. 2000).

The present parameter study also provides a clue to the problem as to why cE's like M32 are apparently so rare (see Table 1). For model 3 with smaller r_{in} (12 kpc) and smaller V_{in} (28 km s^{-1}), both the bulge and stellar disk components com-

Figure 3 shows that a significant fraction (~59%) of the stellar disk is stripped by the M31 strong tidal field within 0.75 Gyr. Thanks to its strongly self-gravitating nature, the bulge loses only a small amount (~19%) of mass and thus can keep its compact morphology during its tidal interaction with M31. The total mass of new stars within the central 5 kpc suddenly becomes larger early in the tidal interaction ($T < 0.2$ Gyr) because the rapid gaseous inflow toward the central region causes efficient star formation. However, the mass fraction of the stellar disk and that of the bulge do not change so significantly within the bulge-dominated region ($r < 2$ kpc): the fractional mass decreases (increases) from 0.55 (0.45) to 0.33 (0.59) for the disk (bulge). The fractional mass of the new stellar component, on the other hand,
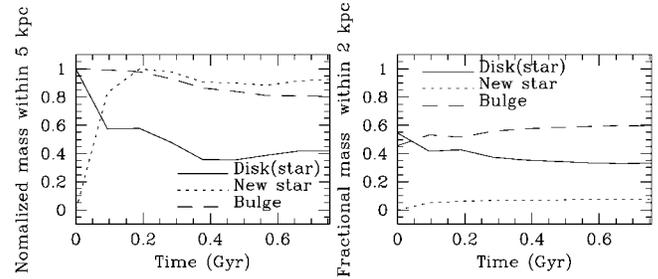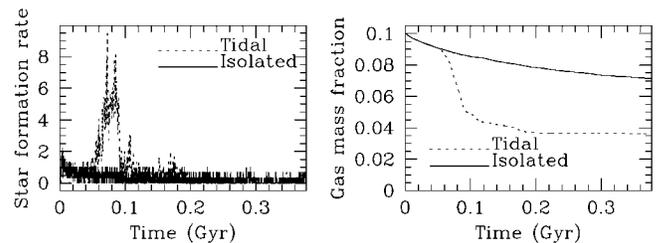

FIG. 4.—Time evolution of star formation in units of $M_\odot$ yr^{-1} (*left*) and that of the gas mass fraction (*right*) for the isolated model (*solid line*) and for the standard model (*dotted line*, represented as a "tidal" model).

pletely disintegrate during the tidal interaction, and accordingly no remnant is left. On the other hand, for model 5 with smaller r_{in} (12 kpc) and larger V_{in} (255 km s^{-1}), the tidal field can only heat up the stellar disk in the vertical direction and consequently transform a spiral galaxy into an S0 galaxy with a thick disk. These results imply that both V_{in} and r_{in} should be within a certain range and thus that the pericenter, r_p, of the orbit of a spiral galaxy plunging into M31 should be within a certain range (r_p approximately several kiloparsecs). The results of models 6, 7, and 8 confirm this, and accordingly the present results strongly suggest that the parameter space for the formation of cE's like M32 is rather narrow. Furthermore, our results demonstrate that S0's can be formed from spiral galaxies with bulges as a result of tidal interaction with their bright host galaxies (see models 5 and 7).

4. DISCUSSION AND CONCLUSION

A new type of subluminous and extremely compact "dwarf galaxy" (the so-called ultracompact dwarf [UCD]) has been discovered recently in an "all-object" spectroscopic survey centered on the Fornax Cluster (Drinkwater et al. 2000, 2001). Drinkwater & Gregg (1998), however, did not find any promising cE candidates (such as NGC 4486B observed in the vicinity of M87) in the same cluster environment. These recent observations have raised the following question on the origin of two different types of compact galaxy, UCDs and cE's (Drinkwater et al. 2000; BCD): are there any physical relationships between these two types? BCD have demonstrated that the strong tidal field of a bright elliptical galaxy can transform a nucleated dwarf (dEn) into a UCD as a result of the dramatic stripping of the outer stellar envelope: only the central compact nucleus can manage to survive after this "galaxy threshing." This result, combined with the present numerical results, therefore suggests that the origin of the difference in physical properties between UCDs and cE's is the difference in the morphological types (i.e., spiral galaxies vs. dEn's) of the precursor galaxies destined to suffer from galaxy threshing. This explanation is consistent with the observational fact that both UCDs and cE's are located preferentially in the vicinity of bright galaxies, where galaxy threshing works more readily. Although no UCDs are currently known around M31, there

may be one in its future. Zinnecker & Cannon (1986) recognized that the star-forming dwarf companion of M31, NGC 205, is comparable to Virgo Cluster nucleated dE galaxies; if its orbit with respect to M31 is rather eccentric, it will be threshed by M31 and leave a UCD or a ω Centauri–like peculiar globular cluster (e.g., G1) with an M_B approximately -12 mag around M31.

A direct observational test for confirming the proposed "threshed spiral" scenario is to investigate whether (1) some of M31's halo globular clusters (GCs) show peculiarities in their spatial distribution and kinematics, such as clumping or streams along M32's orbit and retrograde orbital rotation (with respect to M31) similar or nearly identical to M32's retrograde orbit suggested by Cepa & Beckman (1988), or whether (2) there are any stellar and/or gaseous streams or substructures *well outside* the present orbital plane of M32. M32 is observed to have no GCs (Harris 1991), whereas it should have ∼10–20 given its luminosity (van den Bergh 2000). This fact probably implies that most of the GCs initially associated with M32's bulge are tidally stripped from M32 at the epoch of M32 formation (e.g., van den Bergh 2000). Accordingly, if future photometric and spectroscopic studies, deriving *both* the detailed two-dimensional GC distribution and the radial velocity of each GC with respect to M31, find some GCs located previously on M32's orbit, these would strengthen the possibility of the threshed scenario. Furthermore, the present study predicts that tidally stripped stars can be distributed well outside M32's present orbit. Such low surface brightness stellar components (e.g., the so-called "spaghetti" structures observed in the Galaxy; Morrison et al. 2000) *with old and intermediate ages* may well be observed as substructures in M31's stellar halo if they are projected onto the sky. Therefore, future large systematic surveys of M31's stellar halo light distribution via wide-field CCD imagery on 8 m–class telescopes (e.g., SUBARU with Suprime-Cam) will assess the validity of the proposed threshed spiral scenario.

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