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PROPERTIES OF EARLY-TYPE, DRY GALAXY MERGERS AND THE ORIGIN OF MASSIVE ELLIPTICAL GALAXIES

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ABSTRACT

The luminosity dependence of kinematic and isophotal properties of elliptical galaxies is investigated using numerical simulations of galaxy merging, combined with semianalytical models of hierarchical structure formation. Mergers of spiral galaxies as the only formation mechanism for elliptical galaxies can reproduce neither the kinematic and photometric properties of very massive elliptical galaxies nor the change from rotationally flattened, disky systems to anisotropic, boxy systems with increasing luminosity. We present numerical simulations showing that binary mergers of early-type galaxies open an additional channel for the formation of anisotropic, slowly rotating, boxy elliptical galaxies. Including this channel in a semianalytical model, we can successfully reproduce the observed trend that more luminous giant elliptical galaxies are more boxy and less flattened by rotation. This trend can be more strongly reproduced by suppressing residual gas infall and star formation for galaxies with stellar bulge masses $M_* \geq 3 \times 10^{10}\ M_\odot$. Hence we propose that mergers of early-type galaxies play an important role in the assembly of massive elliptical galaxies.

Subject headings: galaxies: elliptical and lenticular, cD — galaxies: evolution — galaxies: interactions — galaxies: structure — methods: numerical

1. INTRODUCTION

Giant elliptical galaxies show a strong dependence of their kinematic and photometric properties on luminosity (see, e.g., Kormendy & Bender 1996). Traditionally, the kinematics supporting the shape of elliptical galaxies is parameterized by the anisotropy parameter $(v_{\rm maj}/\sigma_0)^*$, which relates the observed ratio of the velocity along the major axis and the central velocity dispersion, $v_{\rm maj}/\sigma_0$, to the value expected for an isotropic rotator $v/\sigma = [\epsilon/(1-\epsilon)]^{1/2}$ with the observed ellipticity ϵ (Binney 1978). Observed slow-rotating ($v_{\rm maj}/\sigma_0 \leq 0.2$) elliptical galaxies in general have $(v_{\rm maj}/\sigma_0)^* \leq 0.5$ (see Fig. 1), and their shape is assumed to be supported by anisotropic velocity dispersions. In the following we call these systems anisotropic ("A"). They tend to be the brightest elliptical galaxies, with boxy isophotes, and have the oldest, most metal-rich stellar populations. The bulk of their stars formed on very short timescales (see, e.g.. Heavens et al. 2004; Thomas et al. 2005; references therein). Low-luminosity elliptical galaxies rotate faster ($v_{\rm maj}/\sigma_0 > 0.2$) and have $(v_{\rm maj}/\sigma_0)^* > 0.5$. They are assumed to be flattened by additional rotation ("R"), have disky (sometimes boxy) isophotes and younger stellar populations, and formed on longer timescales. Recently, observations as well as simulations have shown that disky elliptical galaxies show a significant underlying velocity anisotropy (Binney 2005; Burkert & Naab 2005; Cappellari et al. 2005). In this sense, remnants with $(v_{\rm maj}/\sigma_0)^* > 0.5$ might be partly supported by anisotropic dispersions and partly by intrinsic rotation.

What is the origin of the strong mass dependence of the properties of elliptical galaxies? Does it fit into a scenario in which elliptical galaxies result from major galaxy mergers? While the properties of low-luminosity elliptical galaxies are consistent with their being remnants of early-type spiral mergers (Naab & Burkert 2003, hereafter NB03; Naab & Trujillo 2005), it is, for several reasons, unlikely that high-luminosity elliptical galaxies formed in a similar way: (1) the stellar populations of spirals are too young and metal-poor, and their formation timescales are too long (see, e.g., Heavens et al. 2004; Bell et al. 2005; references therein); (2) very luminous elliptical galaxies are significantly more massive than typical spirals; and (3) numerical simulations indicate that the kinematic and photometric properties of spiral merger remnants are different from the properties of the most massive elliptical galaxies (NB03; Naab & Trujillo 2005). Although equal-mass spiral-spiral mergers can form slowly rotating, boxy remnants (Naab et al. 1999), they do not in general result in a homogeneous family similar to that of bright elliptical galaxies.

Khochfar & Burkert (2003) and Khochfar & Burkert (2005, hereafter KB05) used semianalytical modeling to demonstrate that massive elliptical galaxies should have assembled predominantly in mergers between bulge-dominated, gas-poor (dry) early-type galaxies. Those works concluded that the observed characteristic properties of massive elliptical galaxies might reflect the physics of early-type mergers, which in this case should lead to predominantly boxy, slowly rotating anisotropic systems, independent of the progenitor mass ratio. This would be in contrast to spiral-spiral mergers, which produce boxy, anisotropic systems only if the progenitors have equal masses. The semianalytical models of KB05 predict that early-type mergers also occur at low redshifts. These merger remnants would still appear to be old if gas infall and subsequent star formation were negligible during and after the merger events.

Some numerical simulations agree with the conclusions from KB05. Gas-free mergers of spheroids preserve the fundamental plane (Nipoti et al. 2003; González-García & van Albada 2003; Boylan-Kolchin et al. 2005), and the properties of the remnants are in general similar to those of observed elliptical galaxies (Naab & Burkert 2000; González-García & van Albada 2005). However, a detailed investigation of the isophotal shape and kinematics of dry, early-type merger remnants has been missing up to now.

There is direct observational evidence for the existence of early-type mergers in galaxy clusters (van Dokkum et al. 1999; Tran et al. 2005). Bell et al. (2006) and van Dokkum (2005) also find clear evidence for this process in the field. From a comparison with merger timescales taken from the simulations

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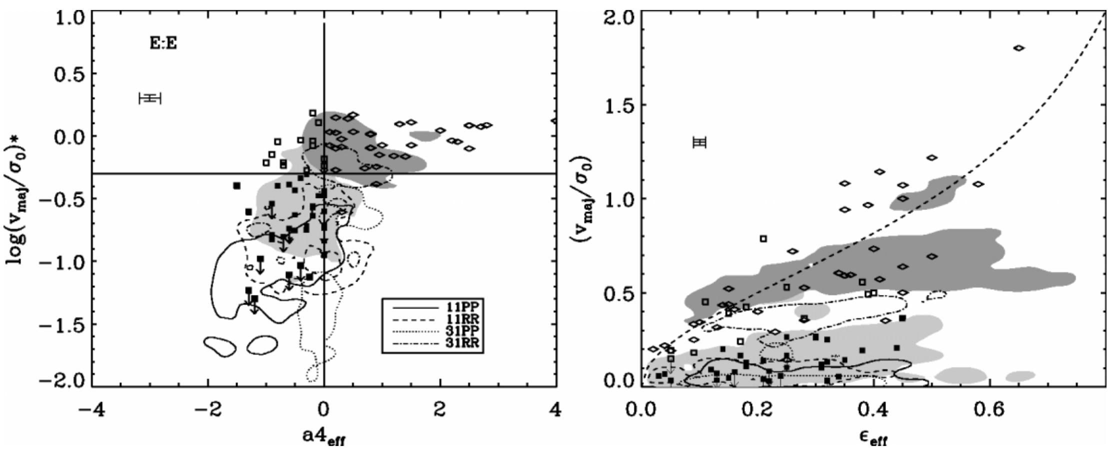

FIG. 1.—*Left*: Isophotal shape $a_{4,\mathrm{eff}}$ vs. anisotropy parameter $(v_{\mathrm{maj}}/\sigma_0)$*. The contours indicate the 80% probability to find a remnant of 1:1 anisotropic (11AA; *solid line*), 1:1 rotationally flattened (11RR; *dashed line*), 3:1 anisotropic (31AA; *dotted line*), and 3:1 rotating (31RR; *dot-dashed line*) early-type mergers in the enclosed area. For every initial galaxy pair, the remnants of the three adopted impact parameters have been combined. The horizontal line at $(v_{\mathrm{maj}}/\sigma_0)^* = 0.5$ separates the anisotropic boxy remnants from the more rotationally flattened disky and boxy elliptical galaxies. *Right*: Ellipticity ϵ_{eff} vs. the ratio of major-axis rotation velocity to central velocity dispersion $(v_{\mathrm{maj}}/\sigma_0)$. For comparison, in both panels the locations of 1:1 (*light gray*) and 3:1 (*dark gray*) spiral merger remnants are indicated by the shaded areas (NB03). The data for observed disky (*diamonds*), very anisotropic boxy (*filled squares*), and less anisotropic boxy (*open squares*) elliptical galaxies were kindly provided by R. Bender. The 11AA, 11RR, and 31AA remnants are consistent with slowly rotating, anisotropic, boxy elliptical galaxies.

presented here, Bell et al. (2006) conclude that a spheroidal galaxy should have undergone typically 0.5–2 early-type major mergers since redshift $z \approx 0.7$. Investigations of the evolution of the luminosity function of elliptical galaxies using various surveys show that the number of early-type galaxies with luminosities $(0.5–2)L_*$ has been growing since $z \approx 1$, accompanied by an increase of the total stellar mass in the early-type galaxy population (Bell et al. 2004; Faber et al. 2005). These observations support a scenario in which massive galaxies assemble a significant amount of their mass even at $z < 1$ by major mergers of early-type galaxies and accretion of satellites rather than by star formation (Drory et al. 2004; Khochfar & Silk 2005).

In this Letter, we present the kinematic and photometric properties of simulated early-type merger remnants as a function of their initial conditions. We combine the outcome of our simulations with semianalytical models and predict the present-day abundance of anisotropic and rotationally flattened elliptical galaxies.

2. THE MERGER MODELS

As prototypical progenitors of mergers between early-type galaxies, we use an anisotropic remnant of a spiral-spiral merger with a mass ratio 1:1 and a rotationally flattened remnant of a 3:1 spiral-spiral merger from the sample of NB03. These objects resemble low- and intermediate-mass elliptical galaxies with respect to their photometric and kinematic properties (NB03; Naab & Trujillo 2005) and therefore can be considered to be very good, but not perfect, models of early-type galaxies. However, the mismatch in higher order moments of the line-of-sight velocity distribution of 3:1 remnants and observed elliptical galaxies (Naab & Burkert 2001) does not influence the conclusions, based on the global kinematics of early-type merger remnants, presented here. We performed second-generation binary mergers with mass ratios of $\eta = 1$ and $\eta = 3$ between anisotropic (11AA, 31AA) and rotating (11RR, 31RR) progenitors. The low-mass progenitor in the unequal-mass mergers contained a fraction $1/\eta$ of the mass and particle number of the high-mass companion in each subcomponent, and its size was scaled as $\eta^{-1/2}$. Particle numbers were the same as in NB03, resulting in 360,000 luminous and 640,000 dark particles for 11AA.

Test simulations indicated that the initial orientation of the early-type progenitors was less important than in spiral-spiral mergers. Therefore, we decided to focus on a variation of the pericenter distances of the mergers, as the analysis of cold dark matter simulations (Khochfar & Burkert 2006) has shown that the impact parameters of major mergers are larger than typically assumed in isolated simulations. For every initial setup, the galaxies approached each other on nearly parabolic orbits with three pericenter distances r_{sep} of 0.5, 2, and 6, where the disk scale length of the more massive first-generation spiral was $h_d = 1$ (see NB03 for all details), resulting in 12 remnants in total. The initial separation was fixed to 30 length units. The simulations were performed with the tree code VINE in combination with the special-purpose hardware GRAPE-5 (Kawai et al. 2000). The gravitational Plummer softening length was the same ($\epsilon_{\mathrm{Plum}} = 0.05$) as for the first-generation spiral mergers. The particle orbits were integrated with a leapfrog integrator and a fixed time step of $\Delta t = 0.02$, which corresponds to ≈0.2% of the half-mass rotation period of the first-generation disks. The total energy was conserved to better than 0.6%. Every remnant was analyzed 10 dynamical timescales after the merger was complete.

The isophotal shape and the kinematics of 500 random projections of each of the 12 merger remnants were analyzed. For each projection, the characteristic ellipticity ϵ_{eff} and isophotal shape parameter $a_{4,\mathrm{eff}}$, as well as the rotational velocity along the major axis v_{maj} and the central velocity dispersion σ_0 were determined as in NB03.

The left panel of Figure 1 shows the location of the remnants in the $(v_{\mathrm{maj}}/\sigma_0)^*$-$a_4$ plane. For every merger pair, the projected remnants of the three orbital geometries have been combined. All 11AA (*solid line*), 11RR (*dashed line*), and 31AA (*dotted line*) remnants have $(v_{\mathrm{maj}}/\sigma_0)^* < 0.5$ and show predominantly boxy isophotes. Only 31AA remnants with a large pericenter distance, $r_{\mathrm{sep}} = 6$, and 11RR remnants with a small pericenter distance, $r_{\mathrm{sep}} = 0.5$, appear to be significantly disky ($a_{4,\mathrm{eff}} \geq$

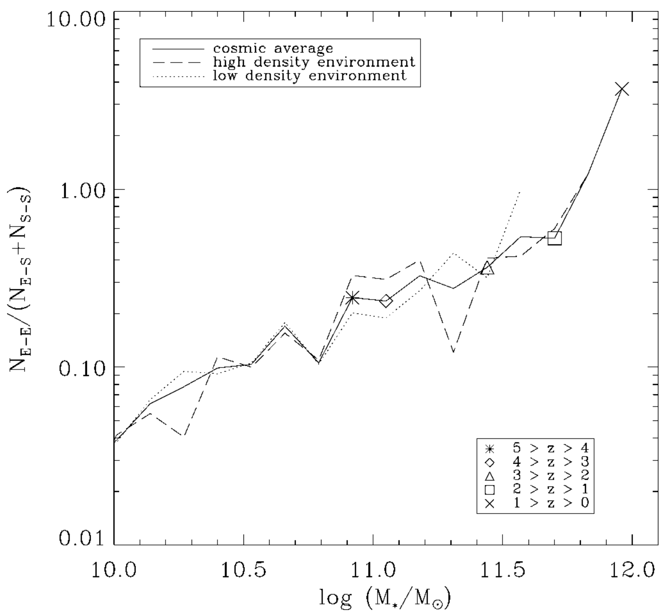

FIG. 2.—Number ratio of last major mergers between two elliptical galaxies (E-E) and the sum of mergers between two spirals (S-S) and a spiral and an elliptical (E-S) galaxy, as a function of stellar mass. The solid line shows the global average, while the dotted and dashed lines show results for field and high-density (cluster) environments, respectively. The symbols show the maximum possible remnant mass formed by E-E mergers at different redshifts for which S-S and E-S mergers still occur.

0.5). The 31RR remnants show distinct properties and have $(v_{maj}/\sigma_0)^* \geq 0.5$ with predominantly disky isophotes.

The distinct kinematic properties of the merger remnants become more evident in the (v_{maj}/σ_0)-ϵ_{eff} plane, which is shown in the right panel of Figure 1. The 11AA, 11RR, and 31AA remnants are slow rotators, in good agreement with observed boxy and anisotropic elliptical galaxies (*filled squares*). The 31RR remnants exhibit stronger rotation $(0.2 < v_{maj}/\sigma_0 < 0.5)$ and are located in the overlap region between boxy and disky elliptical galaxies. This analysis indicates that unequal-mass mergers of early-type galaxies can result in slowly rotating anisotropic systems if the more massive progenitor had similar properties.

3. SIGNIFICANCE OF EARLY-TYPE MERGERS AND THE MASS DEPENDENCE OF ELLIPTICAL GALAXY PROPERTIES

Semianalytical models are useful for quantifying the importance of early-type mergers for elliptical galaxy formation and comparing theoretical models with observations. The model used here is described in detail in KB05. For the present study we adopt the following cosmological parameters: $\Omega_0 = 0.3$, $\Omega_\Lambda = 0.7$, $h = 0.65$, and $\sigma_8 = 0.9$. Early-type galaxies were defined by a bulge-to-total mass fraction of ≥60%. All galaxies with smaller bulge fractions were defined as spirals. As the last major merger determines the final properties of the elliptical galaxies, we show in Figure 2 the predicted number ratio of last elliptical-elliptical (E-E) mergers to the sum of the last elliptical-spiral (E-S) and the last spiral-spiral (S-S) mergers found in our simulations. The importance of E-E mergers steadily increases with increasing remnant mass. Remnants with stellar masses $M_* \gtrsim 6 \times 10^{11}\ M_\odot$ are generally assembled by E-E mergers. Our simulations predict that the $N_{\text{E-E}}/(N_{\text{E-S}} + N_{\text{S-S}})$ versus M_* relation shown in Figure 2 is independent of redshift and environment. The only differences are that elliptical galaxies reach larger masses in denser environments and that at higher redshifts the relation stops at lower remnant masses.

TABLE 1

SUMMARY OF SIMULATIONS

Progenitor	1R	1A	1S	3R	3A	3S
1R	A	A	A	R	A	R
1P	A	A	A	R	A	R
1S	A	A	A	R	A	R

NOTE.—Merger assumptions used in the semianalytical model. "R" and "A" stand for rotationally flattened or anisotropic elliptical galaxies, while "S" represents a spiral galaxy.

A summary of the conditions, which are based on the numerical simulations presented here and in NB03, that lead to anisotropic systems or systems with additional rotation is shown in Table 1, where "S" denotes spiral galaxies. For example, the combination 1R-3A denotes a merger of a rotationally flattened elliptical galaxy with an anisotropic elliptical galaxy that is 3 times more massive. This merger is assumed to lead to an anisotropic ("A") early-type galaxy. All simulations so far show that equal-mass spiral-spiral or elliptical-elliptical mergers predominantly lead to slowly rotating anisotropic systems. It is therefore very likely that this will also be true for equal-mass mixed mergers between spiral and elliptical galaxies. In the case of unequal-mass mixed mergers, we make the conservative assumption that the property of the more massive progenitor dominates the structure of the remnant. We now can classify all the merger remnants in our semianalytical models using the approach of KB05 and Table 1. The result is compared with observations kindly provided by R. Bender[3] in Figure 3 (*dashed line*). As anisotropic systems also form in

[3] Extended data set based on Bender et al. (1992).

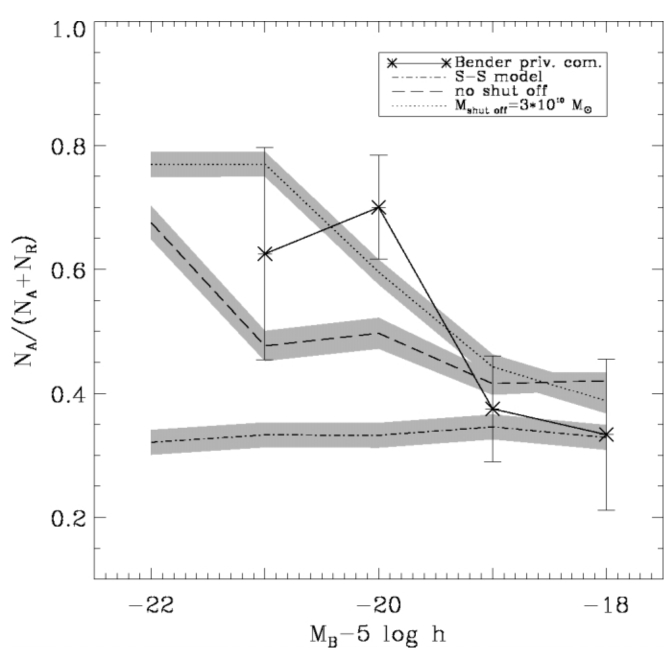

FIG. 3.—Ratio of anisotropic elliptical galaxies to the total number of elliptical galaxies as a function of their B-band luminosity M_B. Stars show observational data provided by R. Bender. The dot-dashed line shows the result for S-S mergers alone, which cannot reproduce the observed trend. The semianalytical model (SAM) predictions including early-type mergers without (*dashed line*) and with (*dotted line*) a shutoff mass scale follow the observed trend. The shaded areas indicate the scatter in the SAMs.

some unequal-mass early-type mergers, the observed trend with galaxy luminosity can be reproduced. An even better agreement (*dotted line*) is found if gas infall and star formation are suppressed above a critical bulge mass of $M_* \geq 3 \times 10^{10}\ M_\odot$, motivated by recent predictions of, for example, Bundy et al. (2005) and Bell et al. (2005). In this case, the growth of stellar disks by gas infall and star formation is suppressed above this critical mass limit, increasing the frequency of early-type mergers and, by this, enhancing the formation rate of anisotropic systems. A model that generalizes the S-S results of NB03 to all mergers (*dot-dashed line*) fails to reproduce the observed trend.

4. CONCLUSIONS

Binary major mergers of spiral galaxies alone do not provide a viable formation mechanism for the whole population of giant elliptical galaxies. In particular, they fail to reproduce the dominance of anisotropic, slowly rotating, boxy elliptical galaxies at high luminosities. A revised major merger scenario that in addition allows major mergers of gas-poor early-type galaxies helps to solve this problem. The individual numerical simulations of collisionless binary early-type mergers presented in this Letter reveal an additional channel for the formation of anisotropic, slowly rotating elliptical galaxies. In the context of hierarchical cold dark matter cosmologies, this additional formation mechanism can successfully reproduce the observed trend that more luminous giant elliptical galaxies are slower rotators and more supported by anisotropic velocity dispersions alone—a trend that matches observations nicely, if residual gas infall and star formation (e.g., the subsequent formation of disks) for galaxies with stellar bulge masses $M_* \geq 3 \times 10^{10}\ M_\odot$ are suppressed. A threshold value like this has been proposed recently (Bundy et al. 2005; Bell et al. 2005). We can also conclude that dissipation becomes less important for the assembly of more massive elliptical galaxies, as proposed by Kormendy & Bender (1996).

The simulations also indicate that early-type merger remnants do preferentially have boxy isophotes (see also Governato et al. 1993). However, individual merger geometries also lead to disky and anisotropic remnants. Further investigations will show whether this higher order effect requires the inclusion of additional physics such as the coalescence of massive black holes.

Our analysis strongly supports a scenario in which major mergers between early-type galaxies play an important role in the assembly of elliptical galaxies even at low redshifts. Provided that the stellar population of the progenitor galaxies was old, even the late assembly of an elliptical galaxy in a major early-type merger will not change this property. Further investigations will have to show to what extent this scenario is in detail consistent with the redshift evolution of elliptical galaxies and local scaling relations such as the color-magnitude relation, the fundamental plane, and the black hole mass–σ relation.

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