STATISTICAL PROPERTIES OF COLLISIONLESS EQUAL- AND UNEQUAL-MASS MERGER REMNANTS OF DISK GALAXIES

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ABSTRACT

We perform a large parameter survey of collisionless $N$-body simulations of binary mergers of disk galaxies with mass ratios of $1:1$, $2:1$, $3:1$, and $4:1$, using the special-purpose hardware GRAPE. A set of 112 merger simulations is used to investigate the fundamental statistical properties of merger remnants as a function of the initial orientation and mass ratio of the progenitor disks. The photometric and kinematical properties of the simulated merger remnants are analyzed. The methods used to determine the characteristic properties are equivalent to the methods used for observations of giant elliptical galaxies. We take projection effects into account and analyze the remnant properties in a statistical way for comparison with observations. The basic properties of the remnants correlate with the mass ratio of the progenitor disks. We find that about 80% of the equal-mass merger simulations lead to slowly rotating merger remnants having $(v/\sigma)^2 < 0.4$. Observers would interpret those objects as being supported by anisotropic velocity dispersions. All $1:1$ remnants show significant minor-axis rotation. Half of all projected $1:1$ remnants show boxy $(a_2 < 0)$ isophotes, and the other half show disky $(a_2 > 0)$ isophotes. A distinct subclass of $4$ out of $12$ initial orientations leads to purely boxy remnants independent of orientation. The $1:1$ mergers with other initial orientations show disky or boxy isophotes, depending on the viewing angle. Remnants with mass ratios of $3:1$ and $4:1$ have more homogeneous properties. They all rotate rapidly (maximum value of $v/\sigma = 1.2$) and show a small amount of minor-axis rotation, consistent with models of isotropic or slightly anisotropic oblate rotators. If observed in projection, they would be interpreted as being supported by rotation. About $90\%$ of the projected $3:1$ and $4:1$ remnants show disky isophotes. The $2:1$ remnants show intermediate properties. Projection effects lead to a large spread in the data, in good agreement with observations. They do not change the fundamental kinematical differences between equal- and unequal-mass merger remnants. The correlation between isophotal twist and apparent ellipticity of every single merger remnant is in good agreement with observations. The amount of twisting strongly depends on the orientation of the remnant but is only weakly dependent on the mass ratio of the merger. The results of this study weaken the disk merger scenario as the possible formation mechanism of massive boxy giant ellipticals, as only equal-mass mergers with special initial orientations can produce purely boxy anisotropic merger remnants. Some orientations of $1:1$ mergers can even lead to disky and anisotropic remnants that are either not observed or would be classified as S0 galaxies based on their morphology. In general, the properties of equal-mass (and $2:1$) merger remnants are consistent with those of the observed population of giant ellipticals in the intermediate-mass regime between low-mass, fast-rotating, disky and bright, massive, boxy giant ellipticals. The $3:1$ and $4:1$ merger remnants, however, are in very good agreement with the class of low-luminosity, fast-rotating giant elliptical galaxies. Binary mergers of disk galaxies are therefore still very good candidates for being the main formation mechanism for intermediate- and low-mass giant ellipticals. The homogeneous class of massive boxy ellipticals most likely formed by a different process.

Subject headings: galaxies: evolution — galaxies: interactions — galaxies: structure — methods: numerical

1. INTRODUCTION

Detailed observations of individual giant elliptical galaxies have shown that they can be subdivided into two groups with respect to their structural properties (Bender, Döbereiner, & Möllenhoff 1988, hereafter BDM88; Bender 1988a; Kormendy & Bender 1996 and references therein). Faint giant ellipticals are isotropic rotators with small minor-axis rotation and disky deviations of their isophotal contours from perfect ellipses. They might contain faint disks that contribute up to $30\%$ to the total light in the galaxy. Therefore, their disk-to-bulge ratios overlap with those of S0 galaxies (Rix & White 1990; Scorza & Bender 1995). Disky ellipticals have power-law inner-density profiles (Lauer et al. 1995; Faber et al. 1997) and show little or no radio and X-ray emission (Bender et al. 1989). Boxy ellipticals, on the other hand, are in general more massive than disky ellipticals. They have box-shaped isophotes and show flat cores. The kinematics of boxy ellipticals is generally more complex than that of disky ellipticals. They rotate slowly, are supposed to be supported by velocity anisotropy, and have a large amount of minor-axis rotation. A number of rotationally supported ellipticals also show boxy isophotes. These systems either are purely boxy (this is
supposed to originate from tidal interactions with nearby massive companions) or show disky isophotes in the inner part and boxy isophotes in the outer part (Nieto & Bender 1989). Occasionally, boxy ellipticals have kinematically distinct cores (Franx & Illingworth 1988; Jedrzejewski & Schechter 1988; Bender 1988b). These cores inhabit flattened, rapidly rotating, disk-or torus-like components dominating the light in the central few hundred parsecs (Bender 1990; Rix & White 1992; Mehler et al. 1998), but they contribute only a few percent to the total light of the galaxy. The fact that these cores are metal-enhanced shows that gas (at least in the inner regions) must have played an important role during their formation (Bender & Surma 1992; Davies, Sadler, & Peletier 1993; Bender 1996; Davies 1996). Boxy ellipticals show stronger radio emission than the average giant elliptical and have high X-ray luminosities, consistent with emission from hot, gaseous halos (Beuing et al. 1999). The distinct physical properties of disky and boxy elliptical galaxies point to the fact that the two types of ellipticals could have different formation histories. It has been argued by Kormendy & Bender (1996) and Faber et al. (1997) that the observed stellar disks and the high-density power-law centers in disky ellipticals are signatures of dissipation during their formation. In this sense, they seem to continue the Hubble sequence from S0’s to higher bulge-to-disk ratios (Kormendy & Bender 1996). Boxy ellipticals, with an even higher bulge-to-disk ratio, show a stronger kinematical decoupling at their centers and no signature of a disk at all. Therefore, the early-type Hubble sequence from S0’s to massive ellipticals might represent galaxies with a disk component embedded in more prominent spheroidal body.

The traditional view on the formation and evolution of giant elliptical galaxies is that they are very old stellar systems and formed very early, at a redshift of more than 2 (Searle, Sargent, & Bagnuolo 1973). After an intensive initial star formation phase, they experienced very little mass evolution (Bruzual A. & Charlot 1993). It has been argued by many authors that the stellar evolution of ellipticals is compatible with pure passive evolution models (Bower, Lucey, & Ellis 1992; Aragón-Salamanca et al. 1993; Bender, Ziegler, & Bruzual 1996; Ellis et al. 1997; Ziegler & Bender 1997) or models with exponentially decaying star formation (Ziegler et al. 1999). Alternatively, hierarchical theories of galaxy formation predict that massive galaxies were assembled relatively late in many generations of mergers of disk-type galaxies or smaller subunits and mass accretion. It has been argued by Kauffmann (1996) and Kauffmann & Charlot (1998) that this merger scenario is consistent with observations of galaxies at different redshifts. The idea that elliptical galaxies can form from mergers of disk galaxies was originally proposed by Toomre & Toomre (1972). Thereafter, the “merger hypothesis” has been investigated in great detail by many authors. For a recent review of current models of spheroid formation, see Burkert & Naab (2003a, 2003b). Negroponte & White (1983), Barnes (1988), and Hernquist (1992) performed the first fully self-consistent merger models of two equal-mass stellar disks embedded in dark matter halos. The remnants were slowly rotating, pressure-supported, anisotropic systems and generally followed an $r^{1/4}$ surface density profile in the outer parts. However, because of phase-space limitations (Carlberg 1986), it was necessary to start with progenitors with massive central bulge components (Hernquist 1993b) to fit the observed de Vaucouleurs profile in the inner parts as well. These simulations showed that the global properties of equal-mass merger remnants resemble those of ordinary, slowly rotating, massive elliptical galaxies. More detailed investigations of isophotal shapes of the merger remnants have shown that the same remnant can appear either disky or boxy when viewed from different directions (Hernquist 1993b), with a trend pointing to boxy isophotes (Heyl, Hernquist, & Spergel 1994; Steinmetz & Buchner 1995). Barnes (1998) and Bendo & Barnes (2000) investigated a sample of disk-disk mergers with a mass ratio of $3:1$ and found that the remnants are flattened and rapidly rotating, in contrast to equal-mass mergers. Naab, Burkert, & Hernquist (1999) investigated the photometric and kinematical properties of a prototypical $3:1$ merger remnant in detail and compared the results to observational data for disky elliptical galaxies. They found an excellent agreement and proposed that rapidly rotating, disky elliptical galaxies can originate from pure, collisionless, $3:1$ mergers, while slowly rotating, pressure-supported ellipticals form from equal-mass mergers of disk galaxies. In this paper, we extend the analysis of Naab et al. (1999). A large number (112) of merger remnants, from a statistically unbiased sample of simulations of mergers between disk galaxies with mass ratios of $1:1, 2:1, 3:1$, and $4:1$, is investigated. This large sample allows a much more thorough investigation of the statistical properties of merger remnants than all previous studies. After a short description of the simulation methods in §2, we investigate the photometric and kinematical properties of the simulated remnants in §3. We discuss the implication of our results on the theory of the formation of elliptical galaxies in §4.

2. THE MERGER MODELS

The spiral galaxies were constructed in dynamical equilibrium using the method described by Hernquist (1993a). We used the following system of units: gravitational constant $G = 1$, exponential scale length of the larger disk $h = 1$ and mass of the larger disk $M_d = 1$. Each galaxy consists of an exponential disk, a spherical, nonrotating bulge with mass $M_b = 1/4$, a Hernquist density profile (Hernquist 1990) with a scale length $r_b = 0.2h$, and a spherical pseudo-isothermal halo with a mass $M_d = 5.8$, cutoff radius $r_c = 10h$, and core radius $\gamma = 1h$.

We followed a sequence of mass ratios of the progenitor disks from $\eta = 1$ to $4$, where $\eta$ is the mass of the more massive galaxy divided by the mass of the merger partner. The equal-mass mergers were calculated adopting in total 400,000 particles, with each galaxy consisting of 20,000 bulge particles, 60,000 disk particles, and 120,000 halo particles. We decided to use twice as many halo particles than disk particles to reduce heating and instability effects in the disk components (Naab et al. 1999). For the mergers with $\eta = 2, 3$, and 4, the parameters of the more massive galaxy were as described above. The low-mass companion contained a fraction $1/\eta$ of the mass and the number of particles in each component, with a disk scale length of $h = (1/\eta)^{1/2}$, as expected from the Tully-Fisher relation (Pierce & Tully 1992).
The $N$-body simulations for the equal-mass mergers were performed by direct summation of the forces using the special-purpose hardware GRAPE-6 (J. Makino, T. Fukushige, & K. Namura 2003, in preparation). With this highly efficient hardware, one force calculation for 400,000 particles takes approximately 11 s. The mergers with mass ratios $\eta = 2, 3,$ and 4 were followed using the newly developed tree code VINE (M. Wetzstein et al. 2003, in preparation), in combination with the GRAPE-5 (Kawai et al. 2000) hardware for which the code was optimized. VINE uses a binary tree, in combination with the refined multipole acceptance criterion proposed by Warren & Salmon (1995). This criterion takes the mass distribution of every node into account. It enables the user to control the absolute force error, which is introduced by the tree construction. We chose a value of 0.001, which guarantees that the error resulting from the tree is smaller than the intrinsic force error of the GRAPE-5 hardware, which is on the order of 0.1%. To compensate for the limited mass resolution of GRAPE-5, we limit the maximum mass of a tree node to 10$^3$ times the minimum particle mass. To further increase the speed of the calculation, we only use GRAPE-5 if forces for more than 50 particles are needed at the same time. Otherwise, we compute the forces on the host computer, as for small particle numbers the communication time between the board and the host computer exceeds the time for the force calculation on the host. With the parameters given above, one force calculation with VINE and GRAPE-5 for 400,000 particles takes approximately 12 s.

We used a gravitational Plummer softening of $\epsilon = 0.05$ and a fixed leapfrog integration time step of $\Delta t = 0.04$. For the equal-mass mergers simulated with direct summation on GRAPE-6, the total energy is conserved; VINE in combination with GRAPE-5 conserves the total energy up to 0.5%.

The galaxies approached each other on nearly parabolic orbits, with an initial separation of $r_{\text{sep}} = 30$ length units and a pericenter distance of $r_p = 2$ length units (the same parameters as in, e.g., Hernquist 1992). A study of orbits of merging dark matter halos in cosmological large-scale simulations by Khochfar (2003) has shown that most of the merging halos are indeed on parabolic orbits. The inclinations of the two disks relative to the orbit plane were $i_1$ and $i_2$, with arguments of pericenter $\omega_1$ and $\omega_2$. In selecting unbiased initial parameters for the disk inclinations, we followed the procedure described by Barnes (1998). For the spin vector of each disk we defined four different orientations, pointing to every vertex of a regular tetrahedron. The initial orientations we used translate to the following set of angles: For the first galaxy

\[ i_1 = (0, -109, -109, -109), \quad \omega_1 = (0, -60, 0, 60). \]

The second galaxy has

\[ i_2 = (180, 71, 71, 71), \quad \omega_2 = (0, -30, 30, 90). \]

These parameters result in 16 initial configurations for equal-mass mergers and 16 more for every mass ratio $\eta = 2, 3,$ and 4, where the initial orientations are interchanged. Following the simple hypothesis that the orientations of the merging disks are independent of each other and independent of their mutual orbital plane, every merger geometry has an equal probability of being realized (Barnes 1998). The orbital parameters are listed in Table 1. In total we simulated 112 mergers. The total computing time for the entire sample was about 1600 hr wall clock time.

For all simulations the merger remnants were allowed to settle into equilibrium approximately 8–10 dynamical times after the merger was complete. Then their equilibrium state was analyzed.

### 3. Photometric and Kinematical Properties of the Remnants

To compare our simulated merger remnants with observations, we analyzed the remnants with respect to observed global photometric and kinematical properties of giant elliptical galaxies, e.g., surface density profiles, isophotal deviation from perfect ellipses, velocity dispersion, and major- and minor-axis rotation. Defining characteristic values for each projected remnant, we followed as closely as possible the analysis described by BDM88.

#### 3.1. Isophotal Shape

An artificial image of the remnant was created by binning the central 10 length units into $128 \times 128$ pixels. This picture was smoothed with a Gaussian filter of standard deviation 1.5 pixels. The isophotes and their deviations from perfect ellipses were then determined using a data reduction package kindly provided by Ralf Bender.

To be confident that a once-determined isophotal shape is characteristic for the remnant and does not change with time, we investigated the time evolution of the ellipticity and the $\alpha_r$ profile, starting $\approx 20$ time units after the merger of the bulge components was complete, and followed the evolution for the next 50 time units. In intervals of 4 time units the luminous part of the remnant was transformed to the principal axes of its moment-of-inertia tensor. The tensor was evaluated using 40% of the most tightly bound particles. The isophotal properties were then analyzed as seen along the minor axis.

The characteristic ellipticity $\epsilon_{\text{eff}}$ for each projection was defined as the isophotal ellipticity at $1.5r_c$. Figure 1 shows the ellipticity profiles for the 3:1 merger remnant with

### Table 1

| Geometry $^a$ | $i_1$ | $\omega_1$ | $i_2$ | $\omega_2$ | $r_p$ | $r_{\text{sep}}$ |
|---------------|-------|------------|-------|------------|-------|-----------------|
| 1/17          | 0     | 180        | 0     | 30         | 30    |                 |
| 2/18          | 0     | 71         | 30    | 2          | 30    |                 |
| 3/19          | 0     | 71         | -30   | 2          | 30    |                 |
| 4/20          | 0     | 71         | 90    | 2          | 30    |                 |
| 5/21          | -109  | -60        | 180   | 0          | 2     | 30              |
| 6/22          | -109  | -60        | 71    | 30         | 2     | 30              |
| 7/23          | -109  | -60        | 71    | -30        | 2     | 30              |
| 8/24          | -109  | -60        | 71    | 90         | 2     | 30              |
| 9/25          | -109  | 0          | 180   | 0          | 2     | 30              |
| 10/26         | -109  | 0          | 71    | 30         | 2     | 30              |
| 11/27         | -109  | 0          | 71    | -30        | 2     | 30              |
| 12/28         | -109  | 0          | 71    | 90         | 2     | 30              |
| 13/29         | -109  | 60         | 180   | 0          | 2     | 30              |
| 14/30         | -109  | 60         | 71    | 30         | 2     | 30              |
| 15/31         | -109  | 60         | 71    | -30        | 2     | 30              |
| 16/32         | -109  | 60         | 71    | 90         | 2     | 30              |

$^a$ For unequal-mass mergers, the orientation of the more massive galaxy is indicated by $i_1$ and $\omega_1$ in geometries 1–16 and by $i_2$ and $\omega_2$ in geometries 17–32.
geometry 10 in intervals of 4 time units, starting at $t = 150$. The ellipticity profile shows little evolution with time, and so does $\epsilon_{\text{eff}}$ (inset). The behavior of this simulation is characteristic of the whole set of simulations.

Following the definition of BDM88 for the global properties of observed giant elliptical galaxies, we determined for every projection the effective $a_4$ coefficient, $a_{4\text{eff}}$, as the mean value of $a_4$ between $0.25r_e$ and $1.0r_e$, with $r_e$ being the projected spherical half-mass radius. In case of a strong peak in the $a_4$ distribution with an absolute value that is larger than the absolute mean value, we chose the peak value. Being characteristic for all merger remnants, Figure 2 shows the $a_4$ profiles at different times for the 3:1 merger remnant with geometry 10. Figure 3 shows the corresponding $a_4$ profiles for the equal-mass remnant with geometry 2. Although the individual $a_4$ profiles differ in details at different time steps, the global characteristic shape is conserved. This is reflected in the time evolution of $a_{4\text{eff}}$ assigned to each remnant at the different time steps, as shown in the insets of Figures 2 and 3. The change in $a_{4\text{eff}}$ due to evolutionary effects (a real change in the isophotal shape and/or a change in three-dimensional shape leading to a different projection angle) is of the same order as the error due to the limited particle number. The bootstrap error bar is shown in the insets of Figures 1 and 2.

These measurements convinced us that the photometric properties of the inner regions (inside $1r_e$) of the merger remnants evolve relatively rapidly into an equilibrium configuration. As the photometric properties do not significantly change with time, they can be used for a further statistical analysis.

To investigate projection effects, we determined for each simulation $a_{4\text{eff}}$ and $\epsilon_{\text{eff}}$ for 500 random projections of every remnant. This resulted in 8000 projections for $\eta = 1$ and 16,000 projections for $\eta = 2, 3,$ and 4.

The normalized histograms of projected ellipticities are shown in Figure 4. For equal-mass mergers, the distribution rises from a small number of projections with zero ellipticity to a peak around $\epsilon_{\text{eff}} = 0.3$ and then falls to zero at $\epsilon_{\text{eff}} = 0.7$. The 2:1 remnants show one peak around $\epsilon_{\text{eff}} = 0.25$ and a strong peak at $\epsilon_{\text{eff}} = 0.45$, falling to zero at $\epsilon_{\text{eff}} = 0.7$. The 3:1 and 4:1 remnants show a flat distribution for small ellipticities, rising to a strong peak around $\epsilon_{\text{eff}} = 0.55$ and 0.6, respectively. No projection leads to ellipticities larger than 0.7.

The distribution function for the isophotal shapes of equal-mass remnants peaks at $a_{4\text{eff}} \approx -0.5$ and declines rapidly for more negative values (Fig. 5). In total, 47% of
the projected 1:1 remnants show disky isophotes, distributed in a broader wing for positive $a_{4\text{eff}}$. For higher mass ratios, the distribution functions have a similar shape but are shifted to more positive values of $a_{4\text{eff}}$. The 2:1 remnants peak at around $a_{4\text{eff}} = 0.5$, and 73% of the projected remnants show disky isophotes. The distributions for 3:1 and 4:1 remnants both peak around $a_{4\text{eff}} \approx 1$. For these systems the fraction of disky projections is about 89% and 91%, respectively.

In addition, the 500 projected values for $a_{4\text{eff}}$ and $\epsilon_{\text{eff}}$ were used to calculate the two-dimensional probability density function for a given simulated remnant to be “observed” in the $a_{4\text{eff}}-\epsilon_{\text{eff}}$ plane. We added up the probability densities, assuming equal weights for every simulation geometry at a given mass ratio. Figure 6 shows the results for mergers with $\eta = 1$, 2, 3, and 4. The contours indicate the areas of 50% (dashed line), 70% (thin solid line), and 90% (thick solid line) probability of detecting a merger remnant with the given properties. Observed data points from BDM88 are overplotted. Filled boxes are for boxy ellipticals with $a_{4\text{eff}} \leq 0$, while open diamonds indicate disky ellipticals with $a_{4\text{eff}} > 0$. The errors were estimated by applying the statistical bootstrapping method (Heyl et al. 1994). The area covered by 1:1 remnants with negative $a_{4\text{eff}}$ is in good agreement with the observed data for boxy elliptical galaxies. In particular, the observed trend for boxier galaxies to have higher ellipticities is reproduced. The disky equal-mass remnants also follow the trend for observed disky ellipticals. Remnants with an $a_{4\text{eff}}$ around zero can have ellipticities slightly higher than those observed. Remnants with $\eta = 2, 3,$ and 4 predominantly populate the region of disky ellipticals, and disky ellipticals also tend to be more flattened. There is a trend for projections with $a_{4\text{eff}} \approx 1$ to have ellipticities slightly higher than those observed (or at a given ellipticity, the remnants are not disky enough). Observed very disky ellipticals with relatively small ellipticities cannot be reproduced.

In summary, there is a clear trend for unequal-mass mergers to produce diskier remnants. Responsible for the disky appearance of the 3:1 and 4:1 remnants is the distribution of the particles of the massive disk. Figure 7 shows the different contributions from the small and large progenitor galaxies and the resulting isophotal map of a characteristic 3:1 merger remnant. The particles originating from the small progenitor accumulate in a torus-like structure that has peanut-shaped or boxy isophotes. In contrast, the dominant luminous material from the larger progenitor still keeps its disklike appearance. In combination, the contribution from the larger progenitor—since it is 3 times more massive—dominates the overall properties of the remnant. This result holds for all 3:1 and 4:1 merger remnants. The more massive disk component is not completely destroyed during the merger event and determines the overall structure of the remnant. For equal-mass mergers, both disks are affected during the merger, and they can lose the memory of their initial state.

The isophotal analysis also provides information about the radial change of the relative orientation of the major axes of the isophotes. In general, the amount of isophotal twist depends on the projection angle. This is demonstrated in Figure 8 for a more elongated and a nearly round projection of a 3:1 merger remnant. To get a quantitative measure for the isophotal twist, we determined the relative position angle $\Delta \Phi$ between the isophotes at $0.5\epsilon_{\text{eff}}$ and $1.5\epsilon_{\text{eff}}$ for every projection of the remnant. Figure 9 shows a comparison of isophotal twists for characteristic remnants with $\eta = 1, 2, 3,$ and 4. The isophotal twist is in general larger for projections that appear nearly round. For ellipticities larger than $\epsilon_{\text{eff}} \approx 0.4$, the isophotal twist is $\Delta \Phi \leq 20^\circ$. The distribution of $\Delta \Phi$ versus $\epsilon_{\text{eff}}$ for random projections of every remnant is consistent with observations of elliptical galaxies (BDM). However, the simulated remnants can show larger isophotal twists at high ellipticities than observed galaxies. In addition, there seems to exist no obvious correlation...
between the mass ratio of the galaxies and the amount of isophotal twist.

3.2. Kinematics

The central velocity dispersion $\sigma_0$ of every remnant was determined as the average projected velocity dispersion of the luminous particles inside a projected galactocentric distance of $0.2r_e$. We defined the characteristic rotational velocity along the major and the minor axes as the projected rotational velocity at $1.5r_e$ and $0.5r_e$, respectively. Figure 10 shows the time evolution for these velocity measurements for a 3:1 merger simulation that is characteristic for all simulations. The derived kinematical properties of the remnants stay nearly constant over a long time period and are therefore a good measurement of the intrinsic kinematics of the simulated remnants. Again, the bootstrap error is of the same order as the change of the measured values with time.

As for the isophotal shape, we computed the statistical kinematical properties of the simulated remnants and compared them with observational data for elliptical galaxies.

The normalized histograms for $v_{\text{maj}}/\sigma_0$ are shown in Figure 11. There is a clear trend for 1:1 mergers to produce slowly rotating ellipticals with $v_{\text{maj}}/\sigma_0 < 0.3$. For 2:1 mergers, the peak value is around $v_{\text{maj}}/\sigma_0 = 0.4$. The 3:1 and 4:1 merger remnants have peaks around $(v_{\text{maj}}/\sigma_0) = 0.6$ and 0.8, respectively. There are indications for a weak secondary peak around $v_{\text{maj}}/\sigma_0 = 1$ for 3:1 and 4:1 remnants.

Figure 12 shows the distribution function in the $(v_{\text{maj}}/\sigma_0)$-$\epsilon_{\text{eff}}$ plane. The area of slowly rotating boxy ellipticals (filled boxes) is almost completely covered by remnants of 1:1 mergers, while 2:1 mergers have rotational properties resembling more rapidly rotating boxy and slowly rotating disky ellipticals. The 3:1 and 4:1 remnants are clearly

![Figure 6](image_url)
rapidly rotating, show high ellipticities, and can be associated with rapidly rotating disky ellipticals. Mergers with an increasing mass ratio produce more rapidly rotating ellipticals with higher ellipticities. All simulated data are in good agreement with observations.

However, there is a trend for the simulated remnants to have maximum ellipticities slightly larger than those observed. Projections with high ellipticities ($\epsilon > 0.5$) show values for $v_{\text{maj}}/\sigma_0$ systematically smaller than those observed. The effect is strongest for equal-mass merger remnants and is discussed in detail below. This indicates that the simulated systems are more strongly supported by anisotropic velocity dispersions than the observed systems, despite significant rotation for 3:1 and 4:1 remnants. Observed ellipticals with $v_{\text{maj}}/\sigma_0 > 1.2$ cannot be reproduced, as was already reported by Cretton et al. (2001).

The minor-axis kinematics of the simulated remnants was measured as the rotation velocity along the minor axis at $0.5r_{\text{eff}}$. The amount of minor-axis rotation was parameterized as $v_{\text{min}}/(v_{\text{maj}}^2 + v_{\text{min}}^2)^{1/2}$ (Binney 1985). Minor-axis rotation in elliptical galaxies, in addition to isophotal twist, has been suggested as a sign for a triaxial shape of the main body of elliptical galaxies (Wagner, Bender, & Möllenhoff 1988; Franx, Illingworth, & de Zeeuw 1991). Indeed, 1:1 mergers show a significant amount of minor-axis rotation (Fig. 13). This is consistent with their mostly triaxial shape and the measured isophotal twist. The 3:1 and 4:1 remnants are more oblate and show weak minor-axis rotation. However, the amount of isophotal twist is comparable to that in equal-mass merger remnants. A detailed analysis of the connection between intrinsic shape, isophotal shape, and internal kinematics is beyond the scope of this paper and needs further investigation.

The anisotropy parameter $(v_{\text{maj}}/\sigma_0)^*$ was defined as the ratio of the observed value of $v_{\text{maj}}/\sigma_0$ and the theoretical value for an isotropic oblate rotator $(v/\sigma)^{\text{theo}} = [\epsilon_{\text{obs}}/(1 - \epsilon_{\text{obs}})]^{1/2}$ with the observed ellipticity $\epsilon_{\text{obs}}$ (Binney 1978). This parameter has been used by observers as a test of whether a given galaxy with observed $v_{\text{maj}}, \sigma_0$, and $\epsilon_{\text{obs}}$ is

![Small progenitor](image1.png)

![Large progenitor](image2.png)

![Both](image3.png)

Fig. 7.—Characteristic isodensity contours of a typical 3:1 merger remnant. The top two panels show the contours for the luminous particles of the smaller and larger progenitors separately. The bottom panel shows the resulting contours of the complete remnant.

![Real isophotes](image4.png)

![Best-fitting ellipses](image5.png)

Fig. 8.—Real isophotes (dotted curves) and best-fitting ellipses (solid curves) for a typical 3:1 merger remnant, in a more elongated (left) and a rounder (right) projection. The major axes of the fitted ellipses are plotted for every isodensity contour. The change of direction of the axes indicates the isophotal twist. The box length is 3 length units.
flattened by rotation \((v_{\text{maj}}/\sigma_0)^* \geq 0.7\) or by velocity anisotropy \((v_{\text{maj}}/\sigma_0)^* < 0.7\) (Davies et al. 1983; Bender 1988a; Nieto, Capaccioli, & Held 1988; Scorza & Bender 1995).

Figure 14 shows the normalized histograms for the \((v_{\text{maj}}/\sigma_0)^*\) values of the simulated remnants. The 1:1 remnants peak around \((v_{\text{maj}}/\sigma_0)^* \approx 0.3\), with a more prominent tail toward lower values. Only about 10% of the projections have \((v_{\text{maj}}/\sigma_0)^* > 0.6\). In contrast, 82% have \((v_{\text{maj}}/\sigma_0)^* < 0.4\) and would clearly be interpreted as being supported by anisotropic velocity dispersion. The 2:1 remnants peak at \((v_{\text{maj}}/\sigma_0)^* \approx 0.5\), with 41% showing \((v_{\text{maj}}/\sigma_0)^* > 0.6\). The 3:1 and 4:1 mergers, with peaks at \((v_{\text{maj}}/\sigma_0)^* \approx 0.6\) and \approx 0.7, are consistent with model predictions of oblate isotropic or slightly prolate rotators. The percentage of projections with \((v_{\text{maj}}/\sigma_0)^* > 0.6\) is 64% and 83%, respectively.

The 3:1 and 4:1 remnants also have predominantly disky isophotes and cover the area populated by observed disky ellipticals in the log\((v_{\text{maj}}/\sigma_0)^* - a_{\text{eff}}\) diagram (Fig. 15).

The 1:1 merger remnants show the most complex behavior. A significant number of the projected remnants lie in a region of disky, anisotropic systems where no elliptical galaxy is observed. On the assumption that a projected remnant clearly fails to resemble an observed elliptical if it has \(a_4 > 0.3\) and \((v_{\text{maj}}/\sigma_0)^* < 0.5\), 28% of the 1:1 remnants would fall into the forbidden regime.

To understand the behavior of equal-mass remnants in more detail, we illustrate the influence of the initial orientation of the progenitor disks on the properties of the merger remnants. We defined mean values of the investigated

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**Fig. 9.** — Isophotal twist \(\Delta \Phi\) vs. ellipticity \(\epsilon_{\text{eff}}\) for characteristic 1:1, 2:1, 3:1, and 4:1 merger remnants. For every mass ratio 500 random projections are shown.

**Fig. 10.** — Time evolution of the characteristic kinematical parameters for a 3:1 remnant: projected central velocity dispersion \(\sigma\) (top), major-axis rotation velocity \(v_{\text{maj}}\) at 1.5 \(r_e\) (middle), and minor-axis rotation velocity \(v_{\text{min}}\) at 0.5 \(r_e\) (bottom). The error bars indicate the bootstrap error.
quantities of all 500 projections for every merger geometry. Thereafter, we divided the equal-mass remnants into four groups of geometries that produce remnants with almost distinct properties: slowly rotating boxy remnants with $v_{\text{maj}}/\sigma_0 < 0.2$ and $\alpha < -0.4$ (group A; geometries 2, 4, 5, and 14); slowly rotating remnants with predominantly disky isophotes having $v_{\text{maj}}/\sigma_0 < 0.2$ and $\alpha > 0.25$ (group B; geometries 1, 8, 9, 11, and 13); modestly rotating remnants ($v_{\text{maj}}/\sigma_0 > 0.2$) that appear to be isotropic, with $\left( v_{\text{maj}}/\sigma_0 \right)^2 > 0.7$ (group C; geometries 7, 10, and 15); and remnants with modest deviations in isophotal shape $-0.2 < \alpha < 0.2$ (group D; geometries 3, 6, 12, and 16). The results are shown in Figure 16.

Remnants of group A are slowly rotating anisotropic systems with purely boxy isophotes. More than 90% of the projected remnants are consistent with observations of boxy, anisotropic, elliptical galaxies. This class of equal-mass merger remnants was sampled by Naab et al. (1999). Most projections of group B show disky isophotes and appear to be anisotropic. Around 60% of the projected remnants of this group fail to fall on the observed correlation. Furthermore, the remnants of this group show too-high ellipticities at low rotation velocities, a behavior already described by Heyl, Hernquist, & Spergel (1996). The shaded regions in Figure 16 indicate the location of the highly elliptical projections ($\epsilon > 0.4$). They dominate the disky, anisotropic branch of “not observed” merger remnants. It is possible that the very elongated projections of group B would be classified as S0 galaxies. Some of them, such as NGC 4550, show weak net rotation and are still very elongated. Geometry 1 produces a very axisymmetric remnant with two counterrotating populations of stars, as observed in NGC 4550 (see, e.g., Pfenniger 1999). However, Rix et al. (1992) argued that a merger origin for this particular galaxy is unlikely, as it would have heated both disks too much.

Group C combines all rotating 1:1 remnants. They appear slightly disky or boxy, depending on the orientation, and are isotropic. It has to be noted that even the disky remnants of this group are consistent with observations, and only 10% of the projections are failures. This group shows a clear connection to the initial conditions, as the spins of the progenitor disks were almost aligned. Projections of group D can have either disky or boxy isophotes and are mostly anisotropic; 35% of the projections fall in the forbidden regime.

4. CONCLUSIONS AND DISCUSSION

We used a large set of $N$-body simulations of collisionless mergers of disk galaxies with mass ratios of $\eta = 1$, 2, 3, and 4 to investigate for the first time the statistical properties of disk merger remnants. In contrast to previous studies, where only projections along the principal axes were investigated, we analyzed a large number of randomly projected merger remnants and compared the results in a consistent way to observations. Galaxies on the sky are also viewed along random lines of sight; therefore, this is the appropriate way of comparison.

We showed that the detailed isophotal and kinematical properties of the simulated merger remnants reach their equilibrium values relatively soon after the merger of the central parts of the galaxies is complete and thereafter do not significantly evolve with time. The high resolution of the simulations made it possible to keep the errors, especially for $a_4$, at a reasonably low value and enabled us to perform a statistical analysis.

The basic result is that the projected kinematical and photometric properties of remnants of major mergers of disk galaxies are in surprisingly good agreement with the observational data for elliptical galaxies. The mass ratio of the progenitor disks determines the global properties of the remnants. The influence of the initial orientation on the remnants is strongest for equal-mass mergers.

Purely boxy anisotropic and slowly rotating remnants with a large amount of minor-axis rotation can only be produced by equal-mass mergers with certain initial orientations. However, if the initial spins of the disks are almost aligned, the remnants appear to be isotropic and disky or boxy, depending on the viewing angle. In total, 28% of all projected 1:1 remnants show properties that are not observed at all. As some of these remnants have high ellipticities and very small $(v_{\text{maj}}/\sigma_0)^2$, they appear to be flattened by strongly anisotropic velocity dispersions. In addition, they mostly show very disky isophotes. As we cannot exclude that mergers with these geometries have occurred, they should be observed, which is not the case. If this controversy is not solved in the future, it might constitute a serious problem for the merger hypothesis. However, if observed, these elongated, disky objects might have been classified as S0 galaxies and have therefore been excluded from the observed sample of bona fide ellipticals.

Based on their diverse properties, the 1:1 remnants more likely resemble the class of intermediate-mass giant ellipticals in the transition region from rotating disky to nonrotating boxy ellipticals. In this regime even boxy rotating galaxies have been observed (Nieto & Bender 1989).

In contrast, 3:1 and 4:1 mergers form a more homogeneous group of remnants. They have preferentially disky isophotes, are rapidly rotating, and show small minor-axis rotation, independent of the assumed projection. In general, the properties are in very good agreement with observations of rapidly rotating, disky ellipticals.
The 2:1 mergers have intermediate properties, with boxy or disky isophotes depending on the projection and the orbital geometry of the merger. Globally, different projection angles and orbits do not change the fundamental properties of 1:1 mergers on the one side and 3:1 and 4:1 mergers on the other side.

In summary, many photometric and kinematical properties of low- and intermediate-mass giant elliptical galaxies can be understood as a sequence of major mergers of disk galaxies with varying mass ratios. The homogeneous group of massive, boxy ellipticals populates the boxy, anisotropic area of the \((v_{\text{maj}}/\sigma_0)^2 - \epsilon_{\text{eff}}\) plane. Their distribution is inconsistent with the distribution of simulated 1:1 remnants. Therefore, they are most likely not remnants of equal-mass mergers of disk galaxies. Boxy and mildly anisotropic remnants are only reproduced by a small subsample of initial conditions. There is no reason why other geometries should have been avoided. It is more likely that massive, boxy ellipticals have formed by other processes, such as mergers of early-type galaxies (Naab & Burkert 2000) or multiple mergers in a group environment (Weil & Hernquist 1996).

The simulations presented here were purely dissipationless, taking into account only the stellar and dark matter components of a galaxy. The importance of gas in galaxy-galaxy mergers and its detailed influence on the structure of elliptical galaxies is not fully understood. Numerical simulations of galaxy mergers including gas by Barnes & Hernquist (1996) and Barnes (1998) have shown that the presence of gas can change the orbital structure and the shape of the merger remnants. As soon as the gas is driven to the center during the merger, the mass concentration seems to be responsible for the destruction of stellar box orbits. This process makes it even more difficult to explain the formation of giant boxy ellipticals by binary disk mergers.

The present study will serve as the basis for a further detailed investigation on the influence of an additional.

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**Fig. 12.**—Rotational velocity along the major axis \(v_{\text{maj}}\) over the central velocity dispersion \(\sigma_0\) vs. the characteristic ellipticity \(\epsilon_{\text{eff}}\) for 1:1, 2:1, 3:1, and 4:1 mergers. The contours indicate the 50% (dotted line), 70% (thin solid line), and 90% (thick solid line) probability of finding a merger remnant in the enclosed area. Values for observed ellipticals are overplotted. Filled boxes and open diamonds indicate data for boxy and disky elliptical galaxies, respectively. Arrows indicate upper limits. The dashed line shows the theoretical value for an oblate isotropic rotator. The error bars were derived by statistical bootstrapping.
dissipative component. Kormendy & Bender (1996) proposed a revised Hubble sequence, with disky ellipticals representing the missing link between the Im-spiral-S0 sequence and boxy ellipticals. They noted that gas infall into the equatorial plane with subsequent star formation could lead to a second disklike subcomponent. Ellipticals with disks could appear disky when seen edge-on and boxy otherwise (Scorza & Bender 1995). Our simulations indeed indicate that a disklike substructure is responsible for producing disky isophotes (see Fig. 6). However, in the present case, the disk is the remnant of the more massive spiral that was not completely destroyed during the minor merger (see also Barnes 1998). Naab & Burkert (2001b) investigated line-of-sight velocity distributions of dissipationless merger remnants and found a velocity profile asymmetry that is opposite to the observed one. They concluded that this disagreement can be solved if ellipticals contain a second disklike substructure that most likely formed through gas accretion. The situation is, however, not completely clear, as another study by Bendo & Barnes (2000) found a good agreement of the observed asymmetries for some cases. Naab & Burkert (2001a) have shown that
extended gas disks can form as a result of a gas-rich, unequal-mass merger. Barnes (2002) recently presented a first detailed set of equal- and unequal-mass merger simulations of gas-rich galaxies resulting in the formation of extended gas disks. His simulations demonstrate a very complex dynamical evolution. It has to be investigated how the presence of gas changes the detailed properties of the remnants in detail. In addition, star formation during the merger will influence the stellar kinematics (see, e.g., Springel 2000) and the stellar populations by adding young, and probably more metal-rich, stars. As metal enrichment provides a further strong observational constraint on the formation history of early-type galaxies (see, e.g., Thomas, Maraston, & Bender 2002), more simulations including dissipation, star formation, and chemical evolution will now be required in order to understand in detail the role of gas in the formation of elliptical galaxies by mergers.

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Fig. 16.—Statistical properties of equal-mass merger remnants divided into four groups (A–D) according to their average properties (see text). The different initial geometries are given in the first row. The contours indicate the 90% probability of finding a projected remnant in the enclosed area. The shaded area in the second column corresponds to the location of projections with ellipticities larger than 0.4.
Franx, M., & Illingworth, G. D. 1988, ApJ, 327, L55
Franx, M., Illingworth, G. D., & de Zeeuw, T. 1991, ApJ, 383, 112
Hernquist, L. 1990, ApJ, 356, 359
———. 1992, ApJ, 400, 460
———. 1993a, ApJS, 86, 389
———. 1993b, ApJ, 409, 548
Heyl, J. S., Hernquist, L., & Spergel, D. N. 1994, ApJ, 427, 165
———. 1996, ApJ, 463, 69
Jedrzejewski, R., & Schechter, P. L. 1988, ApJ, 330, L87
Kauffmann, G. 1996, MNRAS, 281, 487
Kauffmann, G., & Charlot, S. 1998, MNRAS, 297, L23
Kawata, A., Fukushige, T., Makino, J., & Taiji, M. 2000, PASJ, 52, 659
Khochfar, S. 2003, Ph.D. thesis, Univ. Heidelberg
Kormendy, J., & Bender, R. 1996, ApJ, 464, L119
Lauer, T. R., et al. 1995, AJ, 110, 2622
Makino, J., Fukushige, T., & Namura, K. 2003, PASJ, submitted
Mehlert, D., Saglia, R. P., Bender, R., & Wegner, G. 1998, A&A, 332, 33
Naab, T., & Burkert, A. 2000, in ASP Conf. Ser. 197, Dynamics of
Galaxies: From the Early Universe to the Present, ed. F. Combes, G. A.
Mamon, & V. Charmandaris (San Francisco: ASP), 267
———. 2001a, in ASP Conf. Ser. 250, Galaxy Disks and Disk Galaxies, ed.
J. G. Funes & E. M. Corsini (San Francisco: ASP), 451
———. 2001b, ApJ, 555, L91
Naab, T., Burkert, A., & Hernquist, L. 1999, ApJ, 523, L133
Negroponte, J., & White, S. D. M. 1983, MNRAS, 205, 1009
Nieto, J.-L., & Bender, R. 1989, A&A, 215, 266
Nieto, J.-L., Capaccioli, M., & Held, E. V. 1988, A&A, 195, L1
Pfenniger, D. 1999, in IAU Symp. 186, Galaxy Interactions at Low and
High Redshift, ed. J. E. Barnes & D. B. Sanders (Dordrecht: Kluwer),
157
Pierce, M. J., & Tully, R. B. 1992, ApJ, 387, 47
Rix, H.-W., Franx, M., Fisher, D., & Illingworth, G. 1992, ApJ, 400, L5
Rix, H.-W., & White, S. D. M. 1990, ApJ, 362, 52
———. 1992, MNRAS, 254, 389
Scorza, C., & Bender, R. 1995, A&A, 293, 20
Searle, L., Sargent, W. L. W., & Bagnuolo, W. G. 1973, ApJ, 179, 427
Springel, V. 2000, MNRAS, 312, 859
Steinmetz, M., & Buchner, S. 1995, Galaxies in the Young Universe, ed.
H. Hippelein, K. Meisenheimer, & H.-J. Röser (LNP 463; Berlin:
Springer), 215
Thomas, D., Maraston, C., & Bender, R. 2002, Ap&SS, 281, 371
Toomre, A., & Toomre, J. 1972, ApJ, 178, 623
Wagner, S. J., Bender, R., & Möllenhoff, C. 1988, A&A, 195, L5
Warren, M. S., & Salmon, J. K. 1995, Comput. Phys. Commun., 87, 266
Weil, M. L., & Hernquist, L. 1996, ApJ, 460, 101
Ziegler, B. L., & Bender, R. 1997, MNRAS, 291, 527
Ziegler, B. L., Saglia, R. P., Bender, R., Belloni, P., Greggio, L., & Seitz, S.
1999, A&A, 346, 13