SAURON’S CHALLENGE FOR THE MAJOR MERGER SCENARIO OF ELLIPTICAL GALAXY FORMATION

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Received 2007 October 1; accepted 2008 July 1

ABSTRACT

The intrinsic anisotropy δ and flattening ε of simulated merger remnants is compared with elliptical galaxies that have been observed by the SAURON collaboration, and that were analyzed using axisymmetric Schwarzschild models. Collisionless binary mergers of stellar disks and disk mergers with an additional isothermal gas component, neglecting star formation, cannot reproduce the observed trend δ = 0.55ε (SAURON relationship). An excellent fit of the SAURON relationship for flattened ellipticals with ε ≥ 0.25 is, however, found for merger simulations of disks with gas fractions ≥20%, including star formation and stellar energy feedback. Massive black hole feedback does not strongly affect this result. Subsequent dry merging of these merger remnants does not generate the slowly rotating SAURON ellipticals, which are characterized by low ellipticities ε < 0.25 and low anisotropies. These objects therefore might not have been shaped by a final major merger of either early-type galaxies or disks. We show, however, that stellar spheroids resulting from multiple, hierarchical mergers of star-bursting subunits in a cosmological context are in excellent agreement with the low ellipticities and anisotropies of the slowly rotating SAURON ellipticals and their observed trend of δ with ε. The numerical simulations indicate that the SAURON relation might be a result of strong violent relaxation and phase mixing of multiple, kinematically cold stellar subunits, with the angular momentum of the system determining its location on the relation.

Subject headings: galaxies: elliptical and lenticular, cD — galaxies: evolution — galaxies: formation — galaxies: kinematics and dynamics — galaxies: structure — methods: n-body simulations

1. INTRODUCTION

A popular formation scenario for early-type galaxies is the final collision and merger of two roughly equal-mass galaxies with mass ratios between 1:1 and 4:1 in a phase where a large fraction of the total galaxy mass has been assembled. This famous major merger scenario (Toomre & Toomre 1972) has been very successful in explaining observed properties of ellipticals, such as their kinematics, surface density profile, and isophotal shape (Gerhard 1981; Negroponte & White 1983; Barnes 1988, 1990; Barnes & Hernquist 1992; Hernquist 1992, 1993; Burkert 1993; Naab et al. 1999; Cretton et al. 2001; Naab & Burkert 2003; González-García & Balcázar 2005; Jeske et al. 2005; Bournaud et al. 2005; Naab & Trujillo 2006; Naab et al. 2006a; Robertson et al. 2006; Cox et al. 2006). Numerical simulations, for example, have shown that the family of disky, fast rotating ellipticals could result from stellar disk galaxy mergers with unequal mass ratios of 3:1 to 4:1 (Barnes 1998; Bekki 1998; Naab et al. 1999, 2006a; Naab & Burkert 2003; Bournaud et al. 2005) or from gas-rich 1:1 to 2:1 disk mergers where the gas subsequently settles into the equatorial plane of the merger remnant and produces a new stellar disk component (Kochfar & Burkert 2005; Barnes & Hernquist 1996; Naab & Burkert 2001; Barnes 2002; Springel & Hernquist 2005). Boxy, slowly rotating ellipticals, on the other hand, form in stellar disk-disk mergers with mass ratios of 1:1 to 2:1 (Heyl et al. 1994; Naab & Burkert 2003) or from multiple major disk mergers (Weil & Hernquist 1996). Bournaud et al. (2007) showed that repeated minor mergers result in remnant properties very similar to those corresponding to major mergers.

A serious problem of the major merger scenario was the fact that cosmological models do not predict a dependence of the mass ratio of mergers on total galaxy mass or luminosity (Kochfar & Burkert 2003). If, on the other hand, the mass ratio determines the isophotal shape and rotational properties of merger remnants, one would expect that the ratio of the number of fast rotating, disky ellipticals to the number of slowly rotating, boxy systems should be independent of luminosity (Naab et al. 2006b). This is in contrast to observations, which show a strong dependence of isophotal shape and rotational properties on galaxy mass. While massive galaxies are preferentially boxy and slow rotators, lower-mass ellipticals are predominantly disky and fast rotating (for a summary, see Kormendy & Bender 1996). Kochfar & Burkert (2003) argued that this mass dependence of galaxy properties could be explained as a result of differences in the morphologies of the merging progenitors (see, e.g., Kang et al. 2007). Using semianalytical models, they showed that major mergers are dominated by gas-rich disk systems at the low-mass end of ellipticals, while intermediate-mass ellipticals should have formed preferentially from mixed mergers involving a disk and an elliptical galaxy. Finally, the most massive early-type galaxies should have experienced a last elliptical-elliptical merger (dry merger) (Naab et al. 2006b). Mixed mergers have not yet been studied in detail, although according to Kochfar & Burkert (2003) they should be more frequent than dry mergers (see, however, Hopkins et al. 2008a). Dry mergers and their implications for the formation of the red galaxy sequence have, however, received much attention recently (Kochfar & Burkert 2005; Gonzalez-García & van Albada 2005; Faber et al. 2007; Naab et al. 2006b; Boylan-Kolchin et al. 2006).

Further refinement of theoretical models has recently been achieved by including black hole physics in simulations of galaxy mergers and elliptical galaxy evolution. Energetic feedback from central black holes might solve some pending problems of major merger models, such as the suppression of late inflow of cold gas and star formation that would make ellipticals look much bluer than observed (Springel et al. 2005).
In summary, despite several still unsolved questions (e.g., Naab & Ostriker 2007), the major merger scenario has become a popular model to explain the origin of bulge-dominated, spheroidal galaxies (see, e.g., Hopkins et al. 2008b, 2008a). Progress in understanding galactic evolution is often driven by strong interactions between observers and theorists. Increasingly more sophisticated theoretical/numerical models are confronted with continuously improving observations that lead to new theoretical challenges. One example is the SAURON project (Emsellem et al. 2004), which aims to determine the two-dimensional structural and kinematical properties of early-type galaxies using a panoramic integral-field spectrograph. In order to interpret the observations and study the intrinsic galaxy structure, axisymmetric Schwarzschild models are applied to the observations (Cappellari et al. 2006, 2007). The results published so far have revealed interesting fine structures and physical properties which provide new and deeper insight into the origin of galaxies, in particular when compared to simulation (Bendo & Barnes 2000; Jesseit et al. 2007).

In this paper we compare a recently published SAURON analysis of preferentially axisymmetric elliptical galaxies (Cappellari et al. 2007) with the predictions of numerical merger simulations and cosmological models of galaxy formation. Section 2 summarizes the observations. Section 3 shows that simulations of collisionless and gaseous disk-disk mergers, neglecting star formation and stellar feedback, cannot reproduce the observational results. We demonstrate that star formation and stellar energy feedback has a strong effect on the final structure of merger remnants, leading to a good agreement with the SAURON observations of fast-rotating ellipticals. The origin of the round, almost isotropic, slowly rotating SAURON ellipticals is explored in §4. Isolated, dry mergers of ellipticals that formed as discussed in §3 cannot explain these objects. We show, however, that cosmological initial conditions, leading to a series of multiple major and minor mergers, coupled with local starbursts, generate spheroidal stellar systems in very good agreement with the observations. Conclusions follow in §5.

### 2. SAURON RESULTS

Cappellari et al. (2007) analyzed a subsample of 24 elliptical and lenticular galaxies of the SAURON survey, which were biased against triaxiality and consistent with being axisymmetric...
stellar systems. Axisymmetric three-integral Schwarzschild models (Schwarzschild 1979; Cappellari et al. 2006) were used to determine the distribution of stellar orbits. For an investigation of the validity and accuracy of axisymmetric Schwarzschild models in reproducing the intrinsic properties of simulated merger remnants, see Thomas et al. (2007). As SAURON integral-field kinematics was only taken within the effective radius, the Schwarzschild calculations were restricted to a determination of the orbital parameters for the 50% most bound stars in each galaxy. From this, global galactic parameters were derived. The authors found two classes of spheroid-dominated galaxies, one with and one without a significant amount of specific angular momentum (Emsellem et al. 2007). They called these groups slow and fast rotators, respectively. Following Binney (1978), for each galaxy the anisotropy parameter

\[ \delta \equiv \frac{\Pi_{xx} - \Pi_{zz}}{\Pi_{xx}} \]  

(1)

was determined. Here, the z axis coincides with the symmetry and rotation axis of the axisymmetric galaxy,

\[ \Pi_{ii} = \int \rho \sigma_i^2 d^3x \]  

(2)

is the diagonal element of the velocity dispersion tensor in the i-th direction (Binney & Tremaine 1987), \( \sigma_i^2 = \langle v_i^2 \rangle - \langle v_i \rangle^2 \) is the local mean velocity dispersion in the i-th direction, and \( \rho \) is the local stellar density. For axisymmetric systems, \( \Pi_{xx} = \Pi_{yy} \). In addition, the so-called intrinsic ellipticity \( \epsilon_{\text{int}} \) was determined as the edge-on ellipticity of the projected early-type galaxy, corrected for inclination effects.

The red and cyan filled circles in Figure 1 show \( \delta \) versus \( \epsilon_{\text{int}} \) of the slow- and fast-rotating ellipticals of the SAURON sample, respectively. The population of slow rotators is intrinsically quite round (\( \epsilon_{\text{int}} \leq 0.25 \)) and characterized by an almost isotropic velocity dispersion, with \( \delta \leq 0.15 \). In contrast, the fast rotators are in general much flatter (\( \epsilon_{\text{int}} \geq 0.3 \)) and more anisotropic, with \( \delta \geq 0.15 \). This result is in conflict with the standard paradigm that fast-rotating ellipticals are nearly isotropic systems, while slowly rotating ellipticals are strongly anisotropic (Binney 1978). Burkert & Naab (2005) showed that projection effects play an important role for fast rotators, and that even strongly anisotropic stellar systems would appear isotropic when viewed under random projection. The origin of the isotropic, slowly rotating population is, however, puzzling. Despite the fact that the analyzed SAURON sample is still small, Figure 1 clearly reveals a strong correlation between \( \delta \) and \( \epsilon_{\text{int}} \), which can be fitted by the empirical relationship (solid line)

\[ \delta = (0.55 \pm 0.1) \epsilon_{\text{int}}. \]  

(3)

Ellipticals are usually analyzed using the classical \( (V/\sigma) - \epsilon \) anisotropy diagram (Binney 1978, 2005), where \( V \) and \( \sigma \) are the maximum projected rotational velocity and projected central velocity dispersion, respectively, and \( \epsilon \) is the apparent projected ellipticity. Binney (2005) demonstrated that for axisymmetric systems, seen edge-on, the anisotropy is given by

\[ \delta = 1 - \frac{\epsilon}{q(\epsilon)[1 - \alpha(V/\sigma)^2]}, \]  

(4)

where \( \alpha \) measures the shear in the stellar streaming velocity and

\[ q(\epsilon) \equiv \frac{0.5}{1 - \epsilon^2} \frac{\arcsin \epsilon - \epsilon \sqrt{1 - \epsilon^2}}{\epsilon/\sqrt{1 - \epsilon^2} - \arcsin \epsilon}, \]  

(5)

with \( \epsilon = [1 - (1 + \epsilon^2)]^{1/2} \). In general, \( \alpha \) is small. The dashed curves in Figure 1 show the expected correlation between \( \delta \) and \( \epsilon \) for different values of \( V/\sigma \), adopting \( \alpha = 0.15 \) (Cappellari et al. 07). Due to the effect of rotational flattening, \( \epsilon \) increases with increasing \( V/\sigma \) for a given value of \( \delta \). The fast-rotating SAURON ellipticals (cyan circles) cluster around \( V/\sigma \approx 0.5 \) while the slowly rotating sample (red circles) is characterized by \( V/\sigma \lesssim 0.25 \).

Open circles in Figure 1 correspond to objects classified as S0 galaxies. Two of these objects have properties that are similar to fast-rotating ellipticals, indicating either a similar origin or classification problems. Note, however, the three highly elliptical and fast-rotating outliers, which indicate that Sb's are at least sometimes more rotationally dominated than fast-rotating early-type galaxies.

In the next sections we will explore the question of whether these observational results are in agreement with the major merger scenario of early-type galaxy formation.

3. THE ORIGIN OF THE FAST-ROTATING SAURON ELLIPSYLICALS

We start with an analysis of a large sample of collisionless merger remnants of disk galaxies with different mass ratios and initial orientations. The progenitors consisted of a stellar disk, a stellar bulge, and a surrounding dark matter halo. Gas and star formation has been neglected. Details of the initial conditions, the simulations, and the properties of the merger remnants have been presented elsewhere (Burkert & Naab 2003; Naab & Burkert 2003; Khochfar & Burkert 2006; Naab et al. 2006a). There it was shown that equal-mass mergers with progenitor mass ratios of 1:1 to 2:1 produce slowly rotating and often boxy remnants, resembling massive ellipticals, while unequal-mass mergers with mass ratios of 3:1 to 4:1 generate fast-rotating, disky remnants, resembling lower-mass ellipticals.

In order to match the SAURON analysis, \( \delta \) was determined from the 50% most bound stellar particles of the relaxed merger remnants and \( \epsilon_{\text{int}} \) from the edge-on projected stellar distribution. Cappellari et al. (2007) used axisymmetric models where \( \Pi_{xx} = \Pi_{yy} \). One should note, however, that 1:1 mergers in particular are quite triaxial. Our 1:1 mergers have a roughly homogeneous distribution of the ratio \( \Pi_{yy}/\Pi_{xx} \), which lies in the range of \( \Pi_{yy}/\Pi_{xx} = 0.75 \). We therefore use an averaged value of the velocity dispersion in the equatorial plane in order to determine the anisotropy,

\[ \delta \equiv \frac{0.5(\Pi_{xx} + \Pi_{yy}) - \Pi_{zz}}{0.5(\Pi_{xx} + \Pi_{yy})}. \]  

(6)

which in the axisymmetric case reduces to equation (1).

Figure 2 shows the distribution of all collisionless merger remnants in the \( \delta-\epsilon_{\text{int}} \) diagram. In agreement with previous work, 1:1 remnants (red triangles) are slowly rotating \( (V/\sigma \lesssim 0.25) \), consistent with the slow rotators found by the SAURON team. The 2:1–4:1 merger remnants fall into the regime of \( 0.25 \leq V/\sigma \lesssim 0.75 \), consistent with fast-rotating SAURON ellipticals. However, in contrast to the SAURON observations, no correlation of \( \delta \) with \( \epsilon \) is visible. Independent of \( V/\sigma \), \( \epsilon \), or the progenitor mass ratio, collisionless merger remnants are characterized on average by an anisotropy of \( \delta \approx 0.35 \), with a large spread.
This value is close to the anisotropy found for the most flattened, fast-rotating SAURON ellipticals. The disagreement increases, however, for less flattened, slow rotators. On average, even the fast-rotating SAURON ellipticals have substantially lower anisotropies and lower ellipticities than our theoretical models.

The disagreement is largest for slowly rotating systems. Equal-mass (1:1) collisionless merger remnants, despite their slow rotation, cannot reproduce the observed properties of the slow rotators of the SAURON sample, which are much less anisotropic and therefore much less flattened than predicted by the numerical simulations.

One possible explanation for the disagreement between observations and the theoretical models could be that the SAURON collaboration focused especially on axisymmetric systems, characterized by $\Pi_{yy}/\Pi_{xx} \approx 1$. We tested whether this could generate a bias toward preferentially spherical, low-anisotropy systems by investigating the location of our axisymmetric merger remnants with $\Pi_{yy}/\Pi_{xx} \geq 0.9$ in Figure 2. Their distribution turns out not to be different from the complete sample, ruling out such a solution.

Naab et al. (2006a) emphasized the importance of gaseous energy dissipation during galaxy mergers. They studied a set of disk mergers with mass ratios 1:1 and 3:1, including gas with a mass fraction of 10% of the total disk mass. The gas dynamics was followed during the merging process, adopting an isothermal equation of state. Star formation and stellar feedback was neglected. Despite this simplification, Naab et al. (2006a) showed that a dissipative gas component, settling into the galactic center through its gravitational force, has a strong effect on the orbital structure of the merger remnant, leading to asymmetries of the line-of-sight velocity distribution of rotating ellipticals that are in much better agreement with observations than collisionless merger remnants (see also González-García et al. 2006). The anisotropy and ellipticity of the 1:1 and 3:1 merger remnants with 10% gas, however, turns out to be very similar to the distribution of the collisionless merger sample. Clearly, a 10% gas fraction, as expected in evolved disk galaxies, does not solve the problem either.

Ellipticals are in general old systems that formed at a time when disk galaxies were still quite gas-rich. Star formation and stellar as well as central black hole feedback is therefore expected to have played an important role during galaxy mergers (Hopkins et al. 2008b, 2008a). In order to investigate this question, we have started a new series of gas-rich (≥20% gas) disk mergers, using GADGET2 and taking into account star formation as well as stellar and black hole feedback, as described by Springel & Hernquist (2003) and Springel et al. (2005). A
A detailed analysis of these simulations will be presented in a subsequent paper (Johansson et al. 2008). The triangles in Figure 3 show how star formation and energetic feedback affects the anisotropy and ellipticity of the merger remnants. Large triangles correspond to simulations, including black hole accretion, merging, and black hole feedback. Five simulations have been repeated without taking into account black holes. They are represented in Figure 3 by the smaller triangles. For a more detailed investigation of how star formation, energetic feedback, and black hole physics affects the final structure of the merger remnants, Table 1 compares the anisotropies and ellipticities of the collisionless merger simulations (cols. [2] and [3]) with those starting with the same initial geometries and mass ratios, but including 20% of gas, star formation, and stellar and black hole feedback (cols. [4] and [5]). Columns (6) and (7) finally show the results for the simulations where black hole accretion and feedback has been neglected. The initial conditions are shown in the first column of Table 1 and are defined in Table 1 of Naab & Burkert (2003). The merger 3:1/0 corresponds to a 3:1 coplanar merger with 20% gas (Fig. 3, cyan triangle).

![Figure 3](image_url)

**Table 1**

| Mass Ratio/ Geometry | Stellar $\epsilon_{\text{int}}$ (1) | $\delta$ (2) | SF+BH $\epsilon_{\text{int}}$ (3) | $\delta$ (4) | SF $\epsilon_{\text{int}}$ (5) | $\delta$ (6) |
|---------------------|-----------------------------------|-------------|---------------------------------|-------------|----------------|-------------|
| 1:1/7               | 0.49                              | 0.41        | 0.36                            | 0.20        |                 |             |
| 1:1/10              | 0.34                              | 0.24        | 0.29                            | 0.16        | 0.21           | 0.12        |
| 1:1/13              | 0.44                              | 0.38        | 0.27                            | 0.24        | 0.28           | 0.24        |
| 2:1/4               | 0.64                              | 0.42        | 0.60                            | 0.46        |                 |             |
| 2:1/10              | 0.24                              | 0.07        | 0.47                            | 0.37        |                 |             |
| 2:1/14              | 0.52                              | 0.39        | 0.50                            | 0.31        |                 |             |
| 3:1/4               | 0.69                              | 0.47        | 0.63                            | 0.44        | 0.56           | 0.39        |
| 3:1/10              | 0.51                              | 0.14        | 0.55                            | 0.33        | 0.55           | 0.35        |
| 3:1/14              | 0.59                              | 0.42        | 0.61                            | 0.24        | 0.62           | 0.25        |
| 3:1/0               |                                   |             |                                 |             | 0.67           | 0.47        |

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**Fig. 3.**—Same as Fig. 2, but here red and blue large triangles show the location of 1:1 and 3:1 merger remnants with 20% gas, including star formation and black hole accretion as well as energetic feedback from stars and black holes. The smaller triangles show merger simulations without black hole physics (see also Table 1). Cyan triangles show the results of a coplanar disk merger, including star formation, black hole physics, and energetic feedback processes with initially 20%, 40%, and 80% gas, respectively. All data points can be fitted well by a linear relationship of $\delta$ with $\epsilon_{\text{int}}$ shown by the dotted line. It is somewhat steeper than the SAURON relation (solid line). Green circles correspond to cosmological simulations of spheroidal galaxy formation that take into account star formation, but neglect stellar feedback and black hole physics. Filled black circles show five dry equal-mass mergers of merger remnants that were produced from GADGET merger simulations of disks with 20% gas, taking into account star formation and black hole physics. Open circles show the results of 1:1 and 3:1 dry mergers of ellipticals that were generated by collisionless mergers of stellar disks, as discussed in Naab et al. (2006b).
Figure 3 and Table 1 show that star formation and stellar energetic feedback has a strong effect on the anisotropy and ellipticity of merger remnants. We still find a trend of decreasing rotational support, i.e., decreasing $V/\sigma$ with decreasing mass ratio of the progenitor disks. In addition, now the scatter in the $\delta$ versus $\epsilon_{\text{int}}$ diagram is much smaller, and a clear correlation between $\delta$ and $\epsilon_{\text{int}}$ is visible, which can be fitted by a linear relationship (Fig. 3, dotted line)

$$\delta = 0.67\epsilon_{\text{int}},$$

which is somewhat steeper than the SAURON relation (solid line).

It is interesting that when star formation is included, the location of the merger remnants in the $\delta$-$\epsilon_{\text{int}}$ diagram shifts closer to the dotted line, independent of whether they were above this correlation or below it in the collisionless merger case. For example, while the 3:1 merger with initial geometry 10 in the collisionless case formed a remnant that is characterized by $(\epsilon_{\text{int}}/\delta) = (0.51/0.14)$, when star formation and black hole physics are included, it moves this system up to values of $(\epsilon_{\text{int}}/\delta) = (0.55/0.33)$. Neglecting black holes, the values are very similar with $(\epsilon_{\text{int}}/\delta) = (0.55/0.35)$. An other example is the 1:1 merger with geometry 13, which in the collisionless case is located at $(\epsilon_{\text{int}}/\delta) = (0.44/0.38)$, but with star formation shifts down to $(\epsilon_{\text{int}}/\delta) = (0.27/0.24)$, much closer to the dotted line than previously. In general, star formation is the dominant process. As shown by the small triangles in Figure 3 and in Table 1, the effect of black hole accretion and feedback on the structure of the merger remnants is small.

The influence of the initial gas ratio on the results is indicated by the cyan triangles, which show the results of three 3:1 mergers of two coplanar disk galaxies with initial gas baryon fractions of 20%, 40%, and 80%. When the gas fraction is increased, the remnants move along the dotted curve toward smaller ellipticities and anisotropies.

4. THE ORIGIN OF SLOWLY ROTATING, ISOTROPIC, MASSIVE SAURON ELLIPTICALS

The merger simulations of disk galaxies with star formation still cannot explain the almost round and isotropic SAURON ellipticals with $\epsilon \leq 0.2$ and $\delta \leq 0.15$. Final mergers between ellipticals (dry mergers) have been suggested to dominate these slowly rotating red galaxies (Khochfar & Burkert 2003; Faber et al. 2007; Naab et al. 2006b). A strong motivation for the dry merger scenario is the fact that old, red ellipticals have masses that are much larger than typical spiral galaxies, which basically rules out the possibility that their present structure is the result of a final major spiral-spiral merger (Naab & Ostriker 2007).

We investigated the dry merger scenario by remerging some of the GADGET disk-disk merger remnants, discussed in the previous paragraph. As slowly rotating ellipticals tend to form preferentially from equal-mass mergers, we focus here only on 1:1 mergers. The results of five 1:1 early-type mergers are shown by the filled black points in Figure 3. The merger parameters are summarized in Table 2. The progenitors were merger remnants discussed in Table 1, including star formation and black hole feedback. The location of the black points indicates that equal-mass early-type mergers do not naturally produce slowly rotating, isotropic SAURON ellipticals. The data points cluster around $\epsilon_{\text{int}} \approx 0.57$ and $\delta \approx 0.43$, which is close to the relationship between anisotropy and ellipticity (dotted line) found for disk-disk mergers with star formation. From a dynamical point of view, the dry merger remnants are similar to gas-rich disk mergers with star formation. Note, however, that the parameter space is large, and more work will be required in order to clarify whether there exist initial conditions that lead to isotropic dry merger remnants.

Naab et al. (2006b) analyzed the structure of ellipticals formed through dry remerging of ellipticals that were generated from collisionless 1:1 and 3:1 stellar disk mergers, as discussed in § 3. Note that, as shown in Figure 2, the progenitor ellipticals do not lie on the SAURON relation. Nevertheless, it is interesting that remerging of these systems places them nicely on the $\delta$-$\epsilon_{\text{int}}$ relation described by equation (7) (Fig. 3, open circles). Still, these merger remnants are faster rotating, more anisotropic, and more ellipsoidal than the slowly rotating SAURON ellipticals.

Yet another possibility for generating spheroidal ellipticals are multiple mergers in cosmological high-density regions. Naab et al. (2007) investigated the formation of a number of massive galaxies using high-resolution cosmological simulations in a $\Lambda$CDM universe. The calculations were simple, including only photoionization and cooling of the interstellar medium, as well as star formation. AGN and supernova feedback was neglected. In these simulations efficient cooling of gas generated rapid gas infall into smaller dark halo density perturbations, followed by a burst of star formation. At the same time, these substructures merged into more massive spheroidal stellar galaxies, resembling a present-day red giant elliptical. Shock heating in the later phases generated a surrounding hot gaseous halos that suppressed late star formation, leading at the end to a red, old galaxy (Birnboim & Dekel 2003; Birnboim et al. 2007).

The green points in Figure 3 show the location of three spheroidal galaxies presented in Naab et al. (2007), and seven additional galaxies of similar mass simulated in the same manner. The distribution is in excellent agreement with the SAURON observations of red massive ellipticals. Interestingly, the simulations reproduce not only the observed low ellipticities and anisotropies; they also show the same trend of anisotropy with ellipticity as observed.

5. SUMMARY AND DISCUSSION

The numerical simulations discussed in the previous sections have shown that interstellar gas dynamics, star formation, and stellar feedback play a crucial role in reproducing the observed kinematical and isophotal properties of fast rotating, early-type galaxies. The final structure of the merger remnants depends on the initial mass ratio and gas fraction. The remnants are more round, less anisotropic, and more rotationally supported the smaller the mass ratio $M_1/M_2 \geq 1$ of the progenitors, and the larger the initial gas fraction. The dependence of $\delta$ on $\epsilon_{\text{int}}$ is in agreement with the observed trend found in the SAURON sample.

Our isolated binary merger simulations, including dry mergers, do not, however, generate the observed slowly rotating red SAURON ellipticals with small anisotropies and ellipticities. This indicates that the final shape of at least some early-type galaxies might have been determined by other processes. Interestingly,
we find that spheroidal stellar systems that formed in cosmological simulations are round, isotropic, and slowly rotating, in perfect agreement with the SAURON observations. A detailed discussion of elliptical galaxy formation from cosmological initial conditions and the dependence of their structure on, e.g., environment, merger geometry, or merging history is beyond the scope of this paper and will be discussed elsewhere. Another important question that should be investigated in greater detail is the effect of feedback on cosmological early-type galaxy formation, which has been neglected so far. Here we just note that in contrast to isolated binary mergers, in the cosmologically formed ellipticals, minor mergers as well as binary mergers play an important role (see the merging history of the three examples discussed in Naab et al. (2007)). The randomness of the merging history might be the essential additional ingredient that is required in order to produce slowly rotating, isotropic systems. In our cosmological simulations we did not find high-elliptical stellar spheroids. This might be a selection effect. In order to have high numerical resolution, we focused on the most massive systems, with dark matter halo masses of a few $10^{12} M_\odot$. These objects formed preferentially in dense groups, and therefore experienced multiple merging.

Lower mass system forming in more quiescent environments might more likely have had a final binary merger which would be more suitable to generating highly elliptical early-type galaxies, especially for larger mass ratios of $3:1-4:1$.

Despite the fact that merger simulations with star formation lead to a correlation between anisotropy and ellipticity ($\delta \equiv 0.67\varepsilon_{\text{int}}$) that is very similar to that inferred from observations, its origin is not understood. It is interesting that merger remnants appear to move closer toward this relation along lines of constant $V/\sigma$ (i.e., roughly constant specific angular momentum) the stronger the relaxation process. Here, strong relaxation is defined as the relaxation of a group, consisting of several kinematically cold interacting stellar systems that as a result of their mutual interaction break up and generate a kinematically hot stellar remnant. Several conditions could lead to such a violent dynamical process: multiple merging of cold stellar clumps that formed in the starbursting tidal tails of interacting, gas-rich disk galaxies, or cosmological multiple merging of dark matter substructures with embedded stellar systems. The SAURON relation might therefore represent the relaxed and phase-mixed final state of a complex multiple merger history, with the location of the remnant on the relation being determined by its specific angular momentum, which is related to its value of $V/\sigma$. If this is confirmed, we would expect that including feedback in the cosmological simulations will not strongly affect the final structure, as long as the stars still form during the violent merging phase. More theoretical work is required, however, in order to better understand these interesting questions and their connection to early-type galaxy formation.

We thank Michele Cappellari, Jerry Ostriker, and Eric Emerson for interesting discussions. We also thank the referee Brant Robertson for valuable comments. The work was partly supported by the DFG Sonderforschungsbereich 375 ”Astro-Teilchenphysik.” The numerical simulations were run on a local SGI-Altix 3700 Bx2, which was partly funded by the cluster of excellence ”Origin and Structure of the Universe.”

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