The influence of gas on the structure of merger remnants

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ABSTRACT

We present a large set of merger simulations of early-type disc galaxies with mass ratios of 1:1 and 3:1 and 10 per cent of the total disc mass in gas. The internal orbital structure and the kinematic and photometric properties of the remnants are analysed in detail and compared to pure stellar mergers. In contrast to the collisionless case, equal-mass mergers with gas do not result in very boxy remnants which is caused by the suppression of box orbits and the change of the projected shape of minor-axis tube orbits in the more axisymmetric remnants. The isophotal shape of 3:1 remnants and the global kinematic properties of 1:1 and 3:1 remnants are only weakly affected by the presence of gas. 1:1 remnants are slowly rotating, whereas 3:1 remnants are fast rotating and discy. The shape of the stellar line-of-sight velocity distributions (LOSVDs) is strongly influenced by gas. Within the effective radius, the LOSVDs of collisionless remnants have broad leading wings while their gaseous counterparts show steep leading wings, more consistent with observations of elliptical galaxies. We show that this change is also caused by the suppressed populating of box orbits and it is amplified by the formation of extended gas discs in the merger remnants which might eventually turn into stars. If elliptical galaxies have formed from mergers, our results indicate that massive, slowly rotating boxy elliptical galaxies cannot have formed from dissipative mergers of discs. Pure stellar (dry) mergers are the more likely candidates. On the other hand, lower mass, fast rotating and discy ellipticals can have formed from dissipative (wet) mergers of early-type discs. So far, only unequal-mass disc mergers with gas can successfully explain their observed substructure. This is consistent with the revised morphological classification scheme of increasing importance of gas dissipation when moving from boxy to discy ellipticals and then to spiral galaxies, proposed by Kormendy & Bender.

Key words: methods: analytical – methods: N-body simulations – galaxies: elliptical and lenticular, cD – galaxies: evolution – galaxies: formation – galaxies: fundamental parameters.

1 INTRODUCTION

Inspired by the work of Toomre & Toomre (1972), a large number of simulations have been performed to investigate whether giant elliptical galaxies can be formed by binary mergers of disc galaxies. If this formation is correct, the properties of the merger remnants would have to be in agreement with all observed properties of elliptical galaxies: their global kinematic and photometric properties as well as their fine structure. Violent relaxation (Lynden-Bell 1967; Arad & Johansson 2005) of the stellar and dark matter components is the dominant dynamical process in the rapidly varying potential of an ongoing merger. However, it does not completely erase the information about the progenitor galaxies. Therefore we should observe signposts of the formation process in the remnants, e.g. the morphology of the progenitor galaxies or the encounter geometry, both in the dynamics and in the photometric properties. Elliptical galaxies, if they have formed this way, should show similar properties, providing information about the properties of their progenitors.

Collisionless simulations of equal-mass mergers of disc galaxies have been studied in great detail by several authors (e.g. Gerhard 1981; Barnes 1992; Hernquist 1992; Naab & Burkert 2003, hereafter NB03; González-García & Balcells 2005; Jesseit, Naab & Burkert 2005, hereafter JNB05; Naab & Trujillo 2006). The global properties of the remnants are in agreement with observations of giant elliptical galaxies in the intermediate-mass range, e.g. equal-mass remnants are slowly rotating, anisotropic, have boxy or discy isophotes. Unequal-mass mergers are more isotropic and have discy isophotes (NB03). Merger remnants in general have phase-space densities and surface density profiles that resemble observed ellipticals if bulges are added to the progenitor discs (Hernquist, Spergel & Heyl 1993; Naab & Trujillo 2006).
As soon as the kinematics of simulated merger remnants was investigated in more detail, an interesting disagreement with observed elliptical galaxies was revealed. The line-of-sight velocity distributions (LOSVDs) within the effective radius of merger remnants in general show small asymmetric deviations from Gaussian shape. They tend to have a steep trailing wing (Bendo & Barnes 2000; Naab & Burkert 2001b). In contrast, most observed rotating ellipticals clearly show a steep leading wing in their LOSVDs (Bender, Saglia & Gerhard 1994). Theoretically, axisymmetric, rotating one-component systems in fact show such a behaviour (Dehnen & Gerhard 1994). This would indicate that ellipticals are very simple one-component systems that did not form by mergers. It is, however, unlikely that elliptical galaxies are such simple systems (see e.g. Emsellem et al. 2004). An alternative explanation, based on photometric and kinematical observations, is that rotating ellipticals contain embedded large-scale stellar discs (e.g. Rix & White 1990; Scorza et al. 1998; Rix, Carollo & Freeman 1999). A superposition of two distinct components, e.g. a hot spheroidal bulge and a rotationally supported cold disc, can also result in a steep leading wing of the LOSVD (Bender et al. 1994). Naab & Burkert (2001b) showed that embedding an exponential stellar disc artificially in collisionless merger remnants would change the asymmetries in the LOSVDs, leading to a good agreement with observations. Those discs need a scalelength similar to the effective radius of the bulge and 10–20 per cent of its mass.

Such an extended disc naturally forms in merger remnants from high angular momentum gas located in the outer regions of the progenitors after it has been expelled along the tidal arms (Naab & Burkert 2001a; Barnes 2002; Springel & Hernquist 2005; Wetzstein, Naab & Burkert 2005). Gas initially located at smaller radii shocks and falls to the centre of the remnant probably causing a starburst and/or feeding a supermassive black hole (Mihos & Hernquist 1996; Springel, Di Matteo & Hernquist 2005). This gas does not contribute to the extended disc. It has been shown by Bekki (1998) using simulations including gas and star formation that rotating lenticular galaxies with a disc-like component can form from unequal-mass disc mergers. Furthermore, Springel & Hernquist (2005) have demonstrated with a simulation including star formation and feedback that a remnant with a dominant stellar disc can form self-consistently in an equal-mass merger of two gaseous discs. However, those initial conditions might be more typical for high-redshift discs, and for such an extreme case star formation cannot be neglected.

In this paper, we present simulations of disc galaxy mergers with small gas fractions of 10 per cent which are more similar to low-redshift discs. Our aim is to understand the influence of a small dissipative component (which will always exist, even if star formation is considered) on the global structure of mergers remnants. This will help to constrain the importance of additional physical processes, such as star formation, black hole accretion and feedback (e.g. Cox et al. 2005; Springel & Hernquist 2005; Robertson et al. 2006). It has been shown by Barnes & Hernquist (1996) that the presence of gas influences the stellar component of the merging galaxies. Gas that accumulates at the centre of merger remnants changes the central potential and can increase the velocity dispersion of the stars. Robertson et al. (2006) have demonstrated this effect in merger simulations including star formation. In addition, a steeper central potential well results in a more axisymmetric central shape of the remnants (Barnes 1998). At the same time, the fraction of stars on box orbits is significantly reduced and tubes become the dominant orbit family (Barnes & Hernquist 1996). The most reasonable explanation for this behaviour is that systems with steep cusps in their potential cannot sustain a large population of box orbits (Gerhard & Binney 1985; Schwarzchild 1993; Merritt & Fridman 1996; Barnes 1998; Valluri & Merritt 1998).

In this paper, we present a new and more detailed analysis. With respect to resolution, statistical completeness and comparison to observations, our study goes beyond previous investigations of similar simulations (e.g. Negroponte & White 1983; Barnes 1992; Barnes & Hernquist 1996; Bendo & Barnes 2000). We show quantitatively how a dissipative component changes the LOSVDs and the photometric properties of the merger remnants and explain in detail how these changes are connected to the changes of the orbital content of the remnants (see JNB05, for collisionless remnants). In particular, we demonstrate that a dissipative component can explain the origin of the observed asymmetries in the LOSVDs of elliptical galaxies.

This paper is accompanied by a detailed two-dimensional kinematic analysis of the remnants presented here (Jesseit et al. 2006).

The paper is organized as follows. Section 2 presents the details of the simulations. A short overview of observable properties of ongoing mergers is given in Section 3. The intrinsic and projected shapes of the remnants and their orbital content are discussed in Section 4. In Section 5, we show the projected photometric and kinematic properties of the remnants followed by a detailed investigation of the LOSVDs in Section 6. A summary and conclusions follow in Section 7.

2 THE MERGER MODELS

Disc galaxies were constructed in dynamical equilibrium using the method described by Hernquist (1993). The system of units was: gravitational constant $G = 1$, exponential scalelength of the larger progenitor disc $d_0 = 1$ (the scaleheight was $h_z = 0.2$) and mass of the larger disc $M_d = 1$. The discs were exponential with an additional spherical, non-rotating bulge with mass $M_b = 1/3$, a Hernquist density profile (Hernquist 1990) and a scalelength $r_s = 0.2d_0$ and a pseudo-isothermal halo with a mass $M_d = 5.8$, cut-off radius $r_c = 10d_0$ and core radius $\gamma = 1h$. The parameters for the individual components were the same as those for the collisionless mergers presented in NB03. Scaled to the Milky Way, one length unit is 3.5 kpc, one velocity unit is 262 km s$^{-1}$ and the mass unit is $5.6 \times 10^{10} M_\odot$. For this study, we resimulated the full set of 1:1 and 3:1 mergers with an additional gas component in the disc. We replaced 10 per cent of the stellar disc by gas with the same scalelength and an initial scaleheight of $h_{\text{gas}} = 0.1 h$. The gas was represented by smoothed particle hydrodynamics (SPH) particles adopting an isothermal equation of state, $P = \rho$, with a fixed sound speed of $c_s = 0.039$ in velocity units, corresponding to $c_s = 10$ km s$^{-1}$ if scaled to a Milky Way-type galaxy. Assuming an isothermal equation of state implies that additional heat created in shocks, by adiabatic compression and feedback processes is radiated away immediately. It also implies that substantial heating processes prevent the gas from cooling below its effective temperature, e.g. sound speed. Recently, a number of simulations have shown that using an isothermal equation of state is a reasonably good approximation to the interstellar medium in disc galaxies (see e.g. Naab & Burkert 2001a; Barnes 2002; Li, Mac Low & Klessen 2005, and references therein).

We followed mergers of discs with mass ratios of $\eta = 1$ and 3, 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 440 000 particles with each galaxy consisting of 20 000 bulge particles, 60 000 stellar disc particles, 20 000 SPH particles representing the gas component in the disc and 120 000 halo particles. We decided to use twice as many halo particles than disc particles in their potential cannot sustain a large population of box orbits (Gerhard & Binney 1985; Schwarzchild 1993; Merritt & Fridman 1996; Barnes 1998; Valluri & Merritt 1998).
particles to reduce heating and instability effects in the disc components (Naab, Burkert & Hernquist 1999) by encounters between halo and disc particles. For the mergers with $\eta = 3$, the parameters of the more massive galaxy were the same as described above. The low-mass companion contained a fraction of $1/\eta$, the mass and the number of particles in each component, with a disc scalelength (stars and gas) of $h = \sqrt{1/\eta}$, as expected from the Tully–Fisher relation (Pierce & Tully 1992).

The N-body/SPH simulations were performed using the hybrid N-body/SPH tree code VINE (Wetzstein et al., in preparation) with individual time-steps. The gravitational forces were softened with a Spline kernel of $h_{\text{grav}} = 0.05$. The minimal size of the Spline kernel used for computing the SPH properties, $h_{\text{sp}},$ was fixed to the same value. Implicitly, this procedure suppressed gas collapse on scales smaller than the softening scale and prevents numerical instabilities (Bate & Burkert 1997). All simulation have been run on a cluster of 64 1.5 GHz Sun CPUs at the Institute of Astronomy in Cambridge.

The initial discs were run in isolation for two dynamical times to allow the systems to finally settle into an equilibrium state. In the merger, the galaxies approached each other on nearly parabolic orbits with an initial separation of 30 length units and a pericenter distance of two length units. A study of orbits of merging dark matter haloes in cosmological large-scale simulations by Khochfar & Burkert (2006) has shown that a significant number of the merging haloes are indeed on parabolic orbits with a broad distribution of pericenter distances. In this study, we focus on the usually in simulations considered regime of small pericenter distances. In selecting unbiased initial parameters for the disc inclinations, we followed the procedure described by Barnes (1998). The initial orientations for the discs were the same as in NB03, table 1. The merger remnants were allowed to settle into dynamical equilibrium for approximately 30 dynamical time-scales after the merger was complete. Then their equilibrium state was analysed.

### 3 COMMENTS ON MERGER DYNAMICS AND GAS INFLOW

The properties of the initial disc galaxies change dramatically during the interaction. Tidal forces lead to the formation of tidal arms and trigger gas inflow to the centre. The stellar systems are dynamically heated and finally merge into a new type of galaxy. Most investigations have focused on the properties of the final merger remnants. However, recent high-resolution observations of nearby interacting galaxies have made it possible to compare ongoing mergers directly to different phases of simulated interactions (Dasyra et al. 2006a).

It has not been investigated in detail during which phases of the mergers e.g. the central velocity dispersion or the effective radius adjusts to its final value. A detailed knowledge of how important observables evolve helps to constrain measurements of, e.g. the mass ratios of observed disc mergers (Dasyra et al. 2006a), their gas accretion history, or their star formation rates.

We measured the observables, in particular the effective velocity dispersion of the progenitor discs, during the interaction by following every individual galaxy analysing snapshots of the merger in the orbital plane every 10 unit times (approximately every 10 half-mass rotation periods of the more massive disc). To perform the analysis as consistent as possible with observations (see Dasyra et al. 2006a), we computed the effective radius $r_{\text{eff}}$ of every galaxy as the projected spherical half-mass radius of the stellar particles within five length scales only taking particles of the galaxy itself into account. Thereby we avoided unrealistically large values for $r_{\text{eff}}$ when the galaxies overlap. The effective central stellar velocity dispersion $\sigma_{\text{eff}}$ for each galaxy was then computed within $0.5r_{\text{eff}}$ taking all stellar particles into account. To follow the gas accretion on to the centre, we computed the total gas mass within a radius of $r = 0.1, \ M_{\text{gas}}(r < 0.1)$, which is two times the gravitational Spline softening length of the simulations, $h_s = 0.05$.

In Fig. 1, we show the amount of gas accreted on to the centre of each galaxy. Every line corresponds to one disc galaxy. As soon as the galaxies merge (at $t \approx 70$), the two lines of the progenitor galaxies join. In general, equal-mass galaxies merge faster than unequal-mass galaxies. For 1:1 mergers, every galaxy contains $M_{\text{gas}} = 0.1$. After the first encounter between 10 and 60 per cent of the available gas in the progenitor discs is funnelled to the centre. In some cases additional gas, expelled from the partner galaxy, is captured already at early phases of the merger. The exact numbers vary with the encounter geometry. In general, gas transport is more effective if the spin and the orbital angular momentum of the disc is aligned (Barnes 2002). After the galaxies have merged between 50 and
test dynamical mass estimates of observed nearby ultraluminous infrared galaxies (ULIRGs) in interacting pairs (Dasyra et al. 2006a) which all appear to have mass ratios between 1:1 and 3:1. Our results also indicate that merging disc galaxies might already fall on the observed black hole mass–galaxy relation (Tremaine et al. 2002), soon after their first encounter (Dasyra et al. 2006b).

4 INTRINSIC SHAPES AND STELLAR ORBITS OF THE MERGER REMNANTS

The intrinsic shape of a mass distribution is defined by the ratio of its three principal axes. They were determined by diagonalizing the moment of inertia tensor of each merger remnant. The particles were binned according to their binding energy. That ensures that the subsets of particles follow the structure of the remnant naturally (Weil & Hernquist 1996). The triaxiality parameter $T$ is defined as

$$T = \frac{1 - (b/a)^2}{1 - (c/a)^2},$$

where $a$, $b$, and $c$ are the long, intermediate and minor axis, respectively. The shape of merger remnants is closely related to their intrinsic orbital structure as shown by JNB05. In general, minor-axis tubes are more heavily populated in oblate remnants and box orbits are most abundant in remnants triaxial remnants with $T = 0.5$ (see figs 5 and 6 of JNB05). In Fig. 6, we show how the presence of gas influences the intrinsic shapes of the stellar components of the merger remnants. The triaxiality is lowered for almost every remnant due to the influence of gas. 3:1 remnants with gas only reach a maximum triaxiality of $T = 0.2$, while in the collisionless case they can have triaxialities as large as $T = 0.5$. Although the triaxiality of the 1:1 remnants is also lowered, substantially the effect is smaller than that for 3:1 remnants. The more violent merging process can to some extent counter the dissipational influence of the gas. Gas rather makes the remnant more axisymmetric than more flattened (Fig. 6). The ratio between the short and the long axes of the triaxial body $(c/a)$ is only increased by ~10 per cent, making the remnant slightly more spherical. In contrast, for almost all remnants $b/a$ is now close to unity, i.e. the systems are axisymmetric.

The classification of orbits follows the procedure presented in JNB05 (and references therein) and is based on the method developed by Carpintero & Aguilar (1998). We will repeat only the most important steps. After the merger remnant had settled into equilibrium, we froze the particle distribution and computed the potential using the self-consistent field (SCF) method (Hernquist & Ostriker 1992). As initial condition for the integration of the orbits, we took the positions and velocities of the particles at the final snapshot of the simulation. With this method, all orbit classes which exist in general triaxial potentials can be identified. The orbits were classified as minor-axis tubes, outer major-axis tubes, inner major-axis tubes, boxes and boxlets. About 5–10 per cent of all orbits in every remnant could not be classified with this procedure.

Every orbit class has distinct kinematical properties and shapes. Minor-axis tubes are the backbone of oblate and disc-like systems and have a non-vanishing angular momentum around the short axis of the potential. Major-axis tubes are found in prolate or nearly spherical systems with a non-vanishing angular momentum around the long axis. Boxes and boxlets have no mean angular momentum and can be found close to the centre of the potential.

We compared the population of each orbit class averaged over all 1:1 and 3:1 mergers, respectively, for all merger remnants with and without gas. The result is shown in Fig. 7. In both, 1:1 and 3:1
mergers, gas drastically reduces the fraction of box orbits while the fraction of minor-axis tubes increases by a factor of 2–3 (the slightly larger central gas fractions of the simulations with higher halo resolution discussed in the previous section results in an increase of the tube orbit fraction of 3–5 per cent). This confirms the observed trends towards an axisymmetric shape. Major-axis tubes are also depopulated which is consistent with the reduction of the prolateness. Box orbits are still found at the smallest radii, but minor-axis tubes in general start to be the dominant orbit class at smaller radii than in the dissipationless mergers (Fig. 8). This finding is in agreement with Barnes & Hernquist (1996) and Barnes (1998).

The superposition of all stars, which are on different orbits, determines the projected photometric and kinematic properties of the remnants which are investigated in the following sections.

5 GLOBAL PHOTOMETRIC AND KINEMATIC PROPERTIES

We have performed the isophotal and kinematic analysis of 500 random projections of every remnant following the procedure presented in NB03. An artificial image of each projected remnant was created by binning the stars within the central 10 length units into $128 \times 128$ pixel, smoothed with a Gaussian filter of standard deviation 1.5 pixel. The isophotes and their deviations from perfect ellipses were then determined using a data reduction package kindly provided by Ralf Bender. In this section, the analysis was only performed for the stellar particles. In the following, we refer to the stellar particle distribution as collisionless/without gas or dissipative/with gas depending on whether gas was present or not.
Figure 4. Gas mass inside a radius of $r = 0.1$ of the galaxies for 1:1 mergers (top panel) and the large (middle panel) and small (bottom panel) progenitor galaxies of 3:1 mergers as a function of nuclear separation.

The characteristic ellipticity $\epsilon_{\text{eff}}$ for each projection is defined as the isophotal ellipticity at $1.5 r_e$. In Fig. 9, we show the normalized histograms of the ellipticity distribution for the stellar 1:1 and 3:1 remnants with and without gas. The distributions look similar for 3:1 remnants, whereas 1:1 remnants with gas have more projections with small ellipticities as expected if the main stellar body is more axisymmetric. Still, the distributions peak at similar ellipticities as mainly the ratio of the intermediate to the long axis, $b/a$, is affected by the presence of gas (see Section 4).

The effective $a_4$ coefficient, $a_{4,\text{eff}}$, was computed as the mean value of $a_4$ between 0.25 $r_e$ and 1.0 $r_e$, with $r_e$ being the projected spherical half-mass radius. In contrast to NB03, we do not use the maximum value of $a_4$ in case of a peaked distribution which did, however, not change the results. The normalized histograms of the $a_{4,\text{eff}}$ distribution for all 1:1 and 3:1 remnants with and without gas are shown in Fig. 10. In contrast to the collisionless case, the 1:1 remnants with gas do not show a significant number of boxy projections any more. Their deviations from perfect ellipses have decreased. For 3:1 remnants, the effect of the gas is weaker. There are now more projections which are significantly discy, with $a_{4,\text{eff}} > 2$.

Figure 5. Effective stellar velocity dispersion, $\sigma_{\text{eff}}$, of the galaxies for 1:1 mergers (top panel) and the large (middle panel) and small (bottom panel) progenitor galaxies of 3:1 mergers as a function of nuclear separation.

The most important physical reason for the lack of boxy projections for mergers with gas is the different behaviour of minor-axis tube orbits in axisymmetric and triaxial potentials. As we have shown in Section 4, collisionless 1:1 remnants are more triaxial whereas 1:1 remnants with gas are more axisymmetric. Minor-axis tube orbits in triaxial potentials can support a boxy/peanut isophotal shape in the projection along the minor axis and, more importantly, along the long axis (see fig. 11 in JNB05). Minor-axis tubes are the dominant orbit family around the effective radius of the collisionless remnants (see Fig. 8) and therefore are largely responsible for the overall isophotal shape (see NB03 and JNB05). In the more axisymmetric potentials of the remnants with gas, the minor-axis tubes look more elliptical/less boxy or even discy in all projections. This behaviour is qualitatively demonstrated in Fig. 11 for a typical 1:1 remnant. In addition, the fraction of box orbits and boxlets, which can support a boxy shape, at the centre of collisionless remnants (see fig. 11 in JNB05) is significantly reduced (Fig. 8).

The central velocity dispersion $\sigma_0$ of every remnant was determined as the average projected velocity dispersion of the luminous
remnants with gas do not appear boxy any more and cannot explain in the second row. As shown above, the stellar components of 1:1 and 3:1 merger remnants with gas in comparison to the galaxies (Wagner, Bender & Moellenhoff 1988; Franx, Illingworth et al. 1991), we show the location of the remnants in the major-axis rotation has been investigated in a subsequent paper. 3:1 remnants with gas have similar properties to their collisionless counterparts. Remnants of mergers with gas on average appear more discy and are in better agreement with nearby merger remnants and discy elliptical galaxies is significantly better.

In the third row of Fig. 12, we compare the amount of minor-axis rotation as a function of the isophotal shape of the collisionless remnants and the remnants with gas. There is a weak trend for remnants with gas to show less minor-axis rotation than the collisionless counterparts. This finding can be understood as the fraction of major-axis tubes, which are mainly responsible for minor-axis rotation, is on average reduced due to the influence of gas (see Fig. 7).

The last row of Fig. 12 shows the location of the remnants in the \( v_{maj}/\sigma_0 = -\alpha_k \) plane. Here, \( (v_{maj}/\sigma_0)_* \) is the traditional anisotropy parameter (Binney 1978; see Binney 2005 and Burkert & Naab 2005, for a revised version of the anisotropy parameter and its application to \( N \)-body simulations). On an average, the 1:1 remnants with gas have slightly larger values of \( (v_{maj}/\sigma_0)_* \). Boxy and anisotropic remnants which we found for collisionless remnants did not form. In addition, we find more projected gas remnants with small \( (v_{maj}/\sigma_0)_* \) but discy isophotes than for the pure collisionless remnants. In this regime, no observed elliptical galaxies (Rothberg & Joseph 2006) can be found. However, there are some 50 galaxies with similar properties (Rix et al. 1992). A possible connection will be investigated in a subsequent paper. 3:1 remnants with gas have similar properties to their collisionless counterparts. Remnants of mergers with gas on average appear more discy and are in better agreement with observed discy ellipticals and nearby merger remnants.

6 LOSVD ANALYSIS OF THE MERGER REMNANTS

To measure the LOSVDs of a merger remnant, we shifted the densest region of every two-dimensional projection to the origin and placed a slit with a width of 0.4 unit lengths along the apparent long axis of each projected remnant. The slit was then subdivided into grid cells of 0.15 unit lengths. Thereafter, we binned all particles falling within each cell in velocity along the line of sight. The width of the velocity bins was set to a value of 0.2 for line-of-sight velocities \( v_{los} \) in the range \(-4 < v_{los} < 4\). This resulted in 40 velocity bins over the whole velocity interval. Using the binned velocity data, we constructed line-of-sight velocity profiles for each bin along the slit. Subsequently, we parametrized deviations from the Gaussian
shape using Gauss–Hermite basis functions (Gerhard 1993; van der Marel & Franx 1993). The kinematic parameters of each profile \((\sigma, v, h_3, h_4)\) were then determined by least-squares fitting (see Cretton et al. 2001). The large number of simulated stellar particles (> 100 000) guaranteed that at least 1000 particles fall within each bin inside the effective radius. We have analysed three sets of particle distributions: all star particles of the collisionless simulation, the star particles of the simulation with gas and, assuming that all gas particles have transformed into stars, stars and gas particles of the simulation with gas. In the following, we refer to these sets of particles as: collisionless, stars and stars+gas.

As a prototypical example, Fig. 13 shows the observables \(v, \sigma, v/\sigma, h_3\) and \(h_4\) together with the bootstrapping errors as a function of radius for a 3:1 merger remnant. We compare the kinematics of the collisionless remnant with the stars and stars+gas of the simulated remnant with gas. The line-of-sight velocity is only weakly affected by the presence of gas. There is a slightly steeper gradient at the centre for the merger with gas. The velocity dispersion profile (stars+gas) shows a clear signature of the extended gas disc: it decreases faster with increasing radius. At the centre...
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The fourth-order coefficient, $h_4$, characterizes a LOSVD that is more peaked than a Gaussian if positive and less peaked if negative (Fig. 13). For the 3:1 remnant chosen here, $h_4$ appears to be positive at the centre and negative around the effective radius, a feature that is less prominent for simulations with gas. In this paper, we show the results for $h_4$ for completeness; however, we will not discuss it in greater detail.

In Fig. 16, we have summarized the local correlations between $h_3$ and $v/\sigma$ in the range of 0.25–1$r_e$ along the projected major axis for 500 random projections for all 1:1 and 3:1 merger remnants with and without gas. The collisionless 1:1 remnants (left-hand panel) rotate very slowly and are consistent with observations. The asymmetry of the LOSVD of the stars ($h_3$) increases if gas is added to the simulations. Rotating collisionless 3:1 remnants do not show the observed anticorrelation (right-hand panel, shaded area). The corresponding stellar components of the mergers with gas (contours) have larger maximum values of $v/\sigma$ and show stronger asymmetries with a clear indication for a change of tilt. Including the gas (assuming it has transformed into stars after the merger was complete), the distribution for equal-mass remnants becomes weakly tilted, whereas the distribution for 3:1 remnants shows a clear tilt and extends to a local $v/\sigma \approx 1$ in good agreement with observations.

The lower panels of Fig. 16 show the correlation with $h_4$. Most collisionless remnants have positive local values of $h_4$, whereas the remnants with gas show equal amount of positive and negative values. For 3:1 collisionless remnants, there is a trend for regions with higher $v/\sigma$ to have negative $h_4$. Adding gas to the analysis results in an overall shift to more negative values of $h_4$.

7 SUMMARY AND DISCUSSION

We have presented a statistical sample of simulations of disc galaxy mergers with a 10 per cent fraction of gas in the progenitor discs. The properties of the merger remnants have been compared to the properties of a similar set of simulations without gas. The effect of star formation was not included. The presence of a dissipative component changes the shape and the orbital content of the stellar component of the merger remnants. The fraction of box and boxlet orbits which dominate the inner parts of collisionless remnants is significantly reduced if gas is included. The fraction of outer major-axis tubes is reduced as well and inner major-axis tubes disappear completely. In remnants with gas, most stars move on minor-axis tube orbits. The change of orbits is caused by gas that settles at the centre of the remnants where it deepens the potential well at the same time making it more axisymmetric. In this environment, box orbits cannot exist as they are only supported in triaxial potentials. We find that the intermediate axis of the stellar distribution is most strongly affected and the stellar remnants with gas are more axisymmetric.
Figure 12. Global photometric and kinematic properties of the stellar components of 1:1 and 3:1 merger remnants with and without gas. The contours indicate areas of 50 per cent (dotted line), 70 per cent (thin line) and 90 per cent (thick line) probability to detect a merger remnant with gas with the given properties. For comparison, the shaded areas indicate the 50 per cent (dark grey) and 90 per cent (bright grey) probabilities for collisionless remnants. Data for observed boxy (filled squares) and discy (open diamonds) ellipticals have been kindly provided by Ralf Bender. Data for local merger remnants (open green squares) are taken from Rothberg & Joseph (2006). From top to bottom we show: ellipticity, $\epsilon_{\text{eff}}$, versus $v_{\text{maj}}/\sigma_0$ (the theoretical value for a spheroid flattened by rotation is shown by the dashed line); effective isophotal shape, $a_{4\text{eff}}$, versus $\epsilon_{\text{eff}}$, versus the amount of minor-axis rotation, $v_{\text{min}}/\sqrt{v_{\text{maj}}^2 + v_{\text{min}}^2}$, and versus the anisotropy parameter, $(v_{\text{maj}}/\sigma_0)^*$. The stellar components of remnants with gas (in particular 1:1) do not show boxy isophotes any more and the 3:1 remnants with gas are more discy and show less minor-axis rotation.

These results are in good qualitative agreement with the findings of Barnes & Hernquist (1996) and Barnes (1998). However, with respect to resolution, statistical completeness and comparison to observations our study goes beyond previous investigations. The isophotal shape of equal-mass remnants is strongly affected by gas. Around the effective radius, minor-axis tubes – as well as box orbits and boxlets at smaller radii – in the triaxial potential of collisionless remnants support boxy isophotal shapes. In the
remnants with gas, the fraction of box orbits is reduced and the now dominant tube orbits appear more elliptical or even discy. Statistically, equal-mass mergers with gas do not produce boxy remnants, but they still have a small anisotropy parameter which is in conflict with observations of ellipticals. This is only valid in the limiting case of no star formation during the merger. Realistically, equal-mass disc mergers like nearby ULIRGs do experience bursts of star formation (Genzel et al. 1998, 2001). It is, however, still
unclear how much of the available gas is transformed into stars at which stage of the merger. For individual equal-mass merger simulations, it has been shown by Bekki & Shioya (1997) and Springel (2000) that boxy remnants can be formed if the star formation efficiencies were chosen to be high leading to an evolution that is similar to the collisionless case (Naab et al. 1999). Discy remnants form for low efficiencies similar to the results with gas presented here. 3:1 remnants with gas are slightly more discy (see e.g. Bekki 1998, for an unequal-mass merger simulation including star formation) but in general resemble their collisionless counterpart and are in good agreement with observations of discy elliptical galaxies (Bender, Doebereiner & Moellenhoff 1988; Hao et al. 2006) as well as nearby merger remnants (Rothenberg & Joseph 2006). We expect that the effect of star formation on the isophotal shape of unequal-mass remnants is much weaker (see e.g. Bournaud, Jog & Combes 2005).

The shape of the LOSVD of the stars is significantly influenced by the presence of gas. Collisionless remnants have LOSVDs which are close to Gaussian or have broad leading wings. In contrast, the stellar component of mergers with gas shows a clear tendency for steep leading wings. For remnants with a significant amount of rotation (e.g. 3:1 remnants), this results in an anticorrelation between

\( h_3 \) and \( v/\sigma \), especially if the gas component that has formed extended discs is included in the analysis after the merger is complete. This is in good agreement with observations of discy, fast rotating ellipticals (Bender et al. 1994) and might indicate low star formation efficiencies during the merger event itself. The LOSVDs of

\( h_3 \) and \( v/\sigma \) for the same 3:1 remnants as in Fig. 13. The collisionless remnant shows an anticorrelation between for low \( v/\sigma \) and a correlation for the largest values. For the stellar remnant of the merger with gas \( h_3 \) and \( v/\sigma \) is anticorrelated. Including the gas in the analysis leads to a stronger anticorrelation in good agreement with observations. The range of the observational data is indicated by the shaded area.

\[ h_3 \sim v/\sigma \text{, especially if the gas component that has formed extended discs is included in the analysis after the merger is complete. This is in good agreement with observations of discy, fast rotating ellipticals (Bender et al. 1994) and might indicate low star formation efficiencies during the merger event itself. The LOSVDs of} \]
equal-mass merger remnants are also consistent with boxy, slowly rotating ellipticals. If mergers of disc galaxies have indeed formed elliptical galaxies in the not to recent past, our results confirm the scenario of Kormendy & Bender (1996) that gas dissipation becomes more important the more discy the isophotes of early-type galaxies are and the faster they rotate. Some equal-mass merger remnants with gas still have a small anisotropy parameter and discy isophotes. Either this conflict with observations can be solved by efficient star formation during the merger, or it indicates that massive, boxy ellipticals formed in dissipationless mergers from predominantly stellar progenitors which were either early-type disc galaxies or ellipticals themselves (Naab et al. 1999; Khochfar & Burkert 2003, 2005; González-García & van Albada 2005; Naab, Khochfar & Burkert 2006). Recent high-resolution direct numerical simulations of the formation of field elliptical galaxies from cosmological initial conditions indicate that early-type galaxies after they have formed at high redshift during a phase of intensive merging can thereafter grow by accretion of mainly stellar satellites or minor mergers (Naab et al. 2005).

Combining the results from NB03 and the present study, we can conclude that mergers of typical disc galaxies with bulges can have formed giant elliptical of low and intermediate mass in the past. The agreement of kinematic and photometric properties of 1:1 and in particular 3:1 disc mergers with nearby merger remnants is striking. In combination with results from the simulations presented here, Dasyra et al. (2006a) have been able to show that ongoing disc mergers with ULIRG activity have mass ratios between 1:1 and 3:1. Furthermore, the properties of the simulated remnants are in good agreement with the kinematics and isophotal shapes of nearby merger remnants (Rothberg & Joseph 2006). A particularly interesting result is that Rothberg & Joseph (2006) find merger remnants which are discy and anisotropic, a regime that is populated by simulated remnants but not by virialized old elliptical galaxies (see their paper, for a detailed discussion). The direct comparison of real nearby mergers with merger simulations are a powerful tool to constrain theories on elliptical galaxy formation and the effect of star formation and black hole formation (Dasyra et al. 2006b) in the local universe which then can be applied to simulations at all redshift ranges.

In the present simulations, the conversion of gas into stars has not been included and only progenitors with a small gas fraction have been considered, as otherwise neglecting star formation would hardly be justified. We find important signatures of the small gas component in the merger remnants. The question of how stars form and how stellar energetic feedback or central black hole heating affect the multiphase interstellar medium is still poorly understood (for a summary, see e.g. Elmegreen & Scalo 2004), leading to large uncertainties in models of galaxy formation and evolution. Recent simulation, e.g. by Springel et al. (2005) and Di Matteo, Springel & Hernquist (2005), however, demonstrate their importance in understanding the formation of elliptical galaxies in greater details. The orbital content of the remnants will be influenced by the timing of black hole formation and the efficiency of feedback which determines the amount of gas that can make it to the centre leading to the effects presented here. It will be interesting in future work to explore the effect of these processes on the internal orbital structure and projected properties of elliptical galaxies. From a kinematic point of view, disc merger remnants appear very similar to observed ellipticals, although questions regarding the age and metallicity of the stellar populations have to be addressed in the future. Analytical models of disc formation (e.g. Naab & Ostriker 2006) which contain all the information about stellar ages and metallicities of the progenitor discs and semi-analytical modelling (Khochfar & Burkert 2005; Khochfar & Silk 2006) in combination with detailed merger simulations (Naab et al. 2006) can be used to place further constraints on the disc merger hypothesis.

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