Formation and dynamical evolution of galaxies and of their components

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Abstract. From this vast subject, I will pick out and review three specific topics, namely the formation and evolution of bars, the formation of bulges, and the evolution during multiple major mergers.

Bars form naturally in galactic discs. Their evolution is driven by the exchange of angular momentum within the galaxy. This is emitted mainly by near-resonant material in the inner disc (bar), and is absorbed by near-resonant material in the outer disc and in the halo. As a result of this, the bar becomes stronger and rotates slower.

Bulges are not a homogeneous class of objects. Based on their formation history, one can distinguish three types. Classical bulges are mainly formed before the actual disc component, from collapses or mergers and the corresponding dissipative processes. Boxy/peanut bulges are parts of bars seen edge-on. Finally, disc-like bulges are formed by the inflow of material to the center due to bar torques.

Major mergers bring strong and fast evolution and can turn discs into ellipticals. I present results from simulations of multiple mergers in groups of disc or of elliptical galaxies and discuss the orbital anisotropy in the merger remnant.

1. INTRODUCTION

Since reviewing all the formation and evolution processes of galaxies and of their components is an impossible task within the limits set by the time and page allocation of an invited review, I will concentrate here on three specific topics, namely the formation and evolution of bars, the formation of bulges and the evolution during multiple major mergers.

The formation and evolution processes can be distinguished into fast and slow processes, and into internally and externally driven processes (see also Kormendy & Kennicutt 2004). Fast processes occur on time-scales comparable to dynamical times, while slow processes, often referred to as secular processes, have much longer time-scales, of the order of a few Gyrs. Of course, there is no sharp distinction between the two. Major mergers and collapses are prime examples of fast processes, and have been associated with the formation of elliptical galaxies and of some types of bulges. On the other hand, the evolution of bars is a much slower process, with time-scales of the order of Gyrs.

Formation and evolutionary processes can also be distinguished, by their origin, into internally and externally driven processes. Mergers, both minor and major, as well as accretion, are externally driven. On the other hand, collapses, or the secular evolution of bars are internally driven. In some cases, like the formation of spirals and bars, both internal and external processes can be invoked. Obviously, in groups and clusters the effects of the environment are even stronger than for field galaxies.

2. BAR FORMATION AND EVOLUTION

Bars are near-ubiquitous in disc galaxies, as shown by recent near-infrared observations (Eskridge et al. 2000). Furthermore, the fraction of bars with moderate to high strength seems to be near-constant over the last 8 Gyrs (Sheth et al. 2003, Jogee et al. 2004, Elmegreen, Elmegreen & Hirst 2004).

An example of the formation and evolution of a bar component is given in Figures 1 and 2. It is obtained from a $N$-body simulation, similar to those described in Athanassoula and Misiriotis (2002) and Athanassoula (2003). The disc, starting from axisymmetric at $t = 0$ (not shown), forms a bar relatively early on in the simulation. This bar evolves with time and becomes stronger (mainly longer and more massive). Its isodensity contours evolve from elliptical-like to rectangular-like and it acquires a ring which surrounds it, reminiscent of the inner rings in barred galaxies (Athanassoula & Misiriotis 2002). Viewed side-on (i.e. edge-on with the line of sight along the bar minor axis) the bar thickens considerably in the inner parts and by the end of the simulation has formed a characteristic peanut shape. Viewed end-on (i.e. edge-on with the line of sight along the bar major axis) it also develops a central thick component, of the same shape as classical bulges (see subsection 3.1 below).
The maximum around time 50 is due to an episode of spiral formation. I use here the computer units introduced in Athanassoula & Misiriotis (2002), which can differ considerably quantitatively, i.e. the evolution can occur at different time-scales and lead to bars of considerably different strength.

This evolution is due to the exchange of angular momentum within the galaxy. This is emitted by material at near-resonance in the inner disc (bar region) and particularly at the inner Lindblad resonance (see Figure 1 of Athanassoula 2003). It is absorbed by near-resonant material in the outer disc and particularly in the halo (Athanassoula 2002, 2003). As a result, the bar grows stronger (as witnessed in Figures 1 and 2).

A closer look at Figure 1 shows that this bar growth is not necessarily monotonic over the whole evolution time. E.g. the bar is less strong at time 400\(^1\) than at time 300, and then gets stronger again. To follow this quantitatively, I compare in Figure 2 the run of the bar strength and of the peanut strength with time, for two different simulations. In the first case (left panel) the bar grows very abruptly before time 50\(^2\) and then stays nearly at constant amplitude till about time 200. It then drops abruptly up to about time 300 and then shows only a very mild increase with time. It is interesting to compare this with the evolution of the peanut strength (same figure). This increases very abruptly between times 200 and 300, i.e. at the same times when the bar strength decreases. Such a drop of the bar strength can already be seen in Figure 4 of Athanassoula (2002) and in Figures 2 and 4 of Martinez-Valpuesta, Shlosman & Heller (2005), while the antagonism between bar and peanut strength was discussed by Raha et al. (1991), Martinez-Valpuesta & Shlosman (2004) and Martinez-Valpuesta et al. (2005).

This episode of coupled peanut formation and bar decrease need not be unique in the bar evolution history, as discussed in Martinez-Valpuesta et al. (2005) and as shown in the right panel of Figure 4. Here we see clearly two such episodes, one between times 300 and 400 and the second between times 600 and 700.

### 3. BULGES

Two different definitions have been used so far for bulges. Accordingly, the bulge is either

1. a smooth light distribution that swells out of the central part of a disc viewed edge-on, or

2. the extra light in the central part of the disc, above the extrapolated exponential profile fitting the main part of the disc.

Unfortunately, these two definitions are neither equivalent, nor even consistent (see e.g. Bureau et al. 2005 for a discussion). Furthermore, the thus classified ‘bulges’ form a very inhomogeneous class of objects. Based on their formation scenarios, Athanassoula (2005) distinguished three different types of bulges:

#### 3.1. Classical bulges

These are formed by gravitational collapse or by hierarchical merging of smaller objects and the corresponding dissipative gas processes. The formation process is generally fast and sometimes externally driven. It occurs early on in the galaxy formation process, before the present disc was formed. Several versions of this scenario have been elaborated (Carlberg 1984a,b; Steinmetz & Müller 1995; Steinmetz & Navarro 2002; Sommer-Larsen et al. 2003; Noguchi 1999; Immeli et al. 2004; Kauffmann 1996; Kauffmann, Charlot & White 1996).

An alternative view is that classical bulges formed after the present disc, by accretion, e.g. of a small elliptical (Pfenniger 1993; Athanassoula 1999; Aguerri, Balcells & Peletier 2001; Fu, Huang & Deng 2003). Bulges formed in this way should have several similarities to elliptical galaxies, including their photometric radial profiles, their kinematics and their stellar populations (e.g. Davies et al. 1983; Franx 1993; Wyse, Gilmore & Franx 1997; and references therein). Thus, they should be composed of predominantly old stars, they should have predominantly ellipsoidal shapes and should have near-\(r^{-1/4}\) projected density profiles. A typical object in this category is e.g. the Sombrero galaxy (NGC 4594).

#### 3.2. Box/peanut bulges

These objects form during the dynamical evolution of barred galaxies. As discussed in section 2, bars form naturally and relatively fast in disc galaxies and then evolve at a slower rate. The time necessary for the initial bar formation is of order of a few galaxy rotations and, more precisely, depends on the halo-to-disc mass ratio within the main body of the galaxy. As shown in Figures 1 and 2, somewhat after bar formation some of the material in the bar acquires stronger vertical motions and thus reaches larger distances from the equatorial plane. These distances increase with time. Viewed edge-on, this gives a characteristic box/peanut shape. Thus, box/peanut bulges are simply parts of bars seen edge-on.

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1. I use here the computer units introduced in Athanassoula & Misiriotis (2002). By the calibration of that same paper, the computer time unit is \(1.4 \times 10^7\) yrs. Thus, time 400 corresponds to \(5.6 \times 10^8\) yrs.
2. The maximum around time 50 is due to an episode of spiral formation.
Objects formed in this way should have observed morphological, photometrical and kinematical properties that are the same as those of N-body bars seen edge-on (Kuijken & Merrifield 1995; Merrifield & Kuijken 1999; Athanassoula & Bureau 1999; Bureau & Freeman 1999; Chung & Bureau 2004; Bureau & Athanassoula 1999, 2005; Athanassoula 2005). Since they form by rearrangement of disc material, they should be constituted of stellar populations that are similar to those of the inner disc at radii comparable to those of the box/peanut feature. Subsequent star formation in one, or both, of these components can introduce some young stars. The age of the bulk of the stars, however, can be considerably older than the age of the boxy/peanut feature itself. The average size of these features should be of the order of 1 to 3 disc scale-lengths, and can not reach $D_{25}$. This formation scenario has been well worked out in a number of papers describing relevant N-body simulations (e.g. Combes et al. 1990; Raha et al. 1991; Athanassoula & Misiriotis 2002; Athanassoula 2003, 2005; O’Neill & Dubinski 2003; Martinez-Valpuesta & Shlosman 2004; Martinez-Valpuesta et al. 2005). Orbital structure theory predicts that box/peanut bulges should be shorter than the corresponding bars, and this is indeed confirmed both by simulations and by observations (see Athanassoula 2005 for a complete discussion of this issue).

3.3. Disc-like bulges

Contrary to boxy/peanut bulges, the formation scenario of disc-like bulges is not fully worked out, but the general picture is as follows : It is well known that gas will concentrate to the inner parts of the disc under the influence of the gravitational torque of a bar, thus forming an inner disc extending roughly up to the (linear) inner Lindblad resonance, or forming a ring at such radii (e.g. Athanassoula 1992). The extent of this region is of the order of a kpc. When this disc/ring becomes sufficiently massive it will form stars, which should be observable as a young population in the central part of discs. Kormendy & Kennicutt (2004) estimate that the star formu-
FIGURE 2. As in Fig. 1 but for later times. Note that both the disc extent and the bar strength increase considerably with time.

FIGURE 3. Evolution of the bar strength (solid line) and of the peanut strength (dashed line) with time for two simulations. In the left panel, note that the peanut strength increases abruptly with time roughly between times 200 and 300, and that the bar strength decreases during the same time interval. The simulation shown in the right panel has two such episodes. The first one is between times 300 and 400 and the second one between times 600 and 700.
tion rate density in this region is $0.1 - 1 \ M_{\odot} \ yr^{-1} \ kpc^{-2}$, i.e. 1 to 5 orders of magnitude higher than the star formation rate average over the whole disc. This will lead naturally to the formation of a sizeable central disc. Note that disc-like bulges can also be formed in $N$-body simulations with no gas, from inward motions of the disc material. These disc-like bulges, however, will be less massive than those formed by combined stellar and gaseous processes.

Disc-like bulges have properties attributed normally to disc systems and can contain substructures found normally in discs, mainly spirals, rings, bright star-forming knots, dust lanes and even bars, as discussed e.g. in Kor

4. MULTIPLE MAJOR MERGERS AND HALOES OF ELLIPTICALS

The original suggestion (Toomre 1977) that ellipticals form by mergers of disc galaxies has been followed by a number of investigations based partly on $N$-body simulations and partly on observations (see Barnes and Hernquist 1992, and references therein). It is now well established that disc galaxies are embedded in massive and extended haloes (for a review, see Bosma (1999) and references therein). During the merger of two, or more, disc galaxies into an elliptical, the halo components should also merge, and form the dark halo component of the merger remnant, the mass of which should be equal to the sum of the masses of the haloes of the progenitors. Thus, ellipticals should have a similar ratio of total dark to total baryonic mass as discs. This was corroborated by a number of observations, e.g. by X-ray or by gravitational lensing. It thus came as a big surprise when measurements from PNe of the projected velocity dispersion in the outskirts of some elliptical galaxies gave very low values, thus arguing for little or no dark matter in them (Mendez et al. 2001; Romanowsky et al. 2003).

Using $N$-body simulations, Dekel et al. (2005) argued that the trajectories of stars in the outer parts could be very elongated, and thus lead to radially anisotropic velocity dispersions, which could explain the low observed values of the projected $\sigma$. This very interesting proposal was discussed during this meeting both by K. Kuijken and by G. Mamon, and I refer the reader to their contributions for more information on this subject.

How general and how robust is the Dekel et al. prediction of radial orbits? To elucidate this further, I will extend here this discussion to the case of multiple mergers, to which the formation of elliptical galaxies may also be due (Weil and Hernquist 1994, 1996, Athanassoula & Vozikis 1999). I will present preliminary results on the merging of 5 identical galaxies, either 5 disc galaxies, or 5 ellipticals. These simulations have between a couple and a few million particles and include neither gas nor star formation. According to Dekel et al. the stars which formed during the merger should have only about 10 to 15\% lower $\sigma$ than the older stars. The presence of the gas, however, could influence the whole evolution. Our purely stellar models should be adequate for simulating mergings between ellipticals and/or between early type disc galaxies. On the other hand, the Dekel et al. simulations considered Sb-Sc galaxies as progenitors. The present simulations are thus in all respects very different from those of Dekel et al. and it is interesting to check whether they also produce merger remnants with orbital structure biased towards radial orbits. A more general discussion of these simulations will be presented elsewhere (Athanassoula 2006, in preparation).

Multiple mergers are dynamically more complicated than pair mergers. Indeed, multiple mergers can be considered as a sequence of pair mergers, of types S + S, E + E, or S + E, where S denotes a disc galaxy and E an elliptical. But they can also be near-simultaneous mergers of all the initial galaxies, i.e. considered as an extreme example of a clumpy collapse. Figure 4 shows the result shortly after a multiple merger and reveals the existence of many structures and particularly of many tails. Note
FIGURE 4. A multiple merging. Note the large number of features, and in particular a rather spectacular tail-like feature which contains a number of massive clumps which could later become dwarf ellipticals.

I measured the velocity dispersion radial profiles in such remnants after their fast evolution has subsided and some quasi-equilibrium has been reached. Calculating the same radial profiles at later times gives similar results (see also Fig. 8 of Dekel et al. 2005). I then calculated the anisotropy parameter $\beta$, defined as

$$\beta = 1 - 0.5\left(\sigma_\theta^2 + \sigma_\phi^2\right)/\sigma_r^2,$$

where $\sigma_r$, $\sigma_\theta$, and $\sigma_\phi$ are the components of the velocity dispersion in spherical coordinates. Isotropic cases, with $\sigma_r = \sigma_\theta = \sigma_\phi$ gives $\beta = 0$. Models with purely circular orbits ($\sigma_r = 0$) have $\beta = -\infty$. Finally, models with purely radial orbits ($\sigma_\theta = \sigma_\phi = 0$) give $\beta = 1$.

I then obtained for each simulation the average $\beta$ value, $\langle \beta \rangle$, for the region between 2 and 5 effective radii. Figure 5 shows the histogram of these $\langle \beta \rangle$ values. Note that there is a spread of $\langle \beta \rangle$ values between $-0.8$ and $0.6$. This is much larger than the spread of values found by Dekel et al. (2005) in their simulations of pair mergers (roughly between 0.2 and 0.75), and, particularly, contains examples with a large fraction of near-circular orbits. To investigate this further I give, in the same figure, the same histogram but now only the simulations starting from a group of elliptical galaxies (hatched area in the figure). It is clear that all but one of the simulations that give remnants with a velocity distribution which is biased towards circular-like orbits, rather than towards near-radial ones, have elliptical progenitors. On the other hand, simulations starting with disc galaxies only behave in a way similar to that found by Dekel et al. for the merger remnants from two equal mass spirals; although the $\langle \beta \rangle$ values found here are, on average, somewhat smaller. Note that Dekel et al. (2005) also discuss one simulation in which the progenitors had initially a classical bulge and find that this reduces $\beta$. The extrapolation of this result to mergers between ellipticals is in agreement with the results presented here.
So what causes these differences in the orbital structure of the remnant? Since I have a number of simulations, I decided to search for the parameter(s) in the initial conditions, or in the evolutionary history that would best account for the resulting orbital distribution. After a number of trials, I found that the average time between consecutive mergings was the best indicator. This is part of the evolutionary history of the group. Indeed, if this time is large, then the merging history can be considered as a sequence of pair mergings, initially D + D, and then D + E, or E + E. Inversely, if the average time between mergings is short, then the next merging occurs before the previous one has had time to settle and sometimes even when it is still on-going.

In Figures 6, 7 and 8 I plot $\langle \beta \rangle$ as a function of the average time between mergings, for simulations starting with ellipticals, simulations starting with discs and all simulations together, respectively. The first two plots show a very clear trend. In simulations in which the mergings followed each other closely in time (i.e. have small $\langle \Delta T \rangle$) $\langle \beta \rangle$ is sometimes positive (6 cases out of 11) and sometimes negative (5 cases out of 11), with many cases being near zero. Such remnants should have near-isotropic velocity distributions. On the other hand, simulations in which the mergings are widely spaced in time (i.e. have large values of $\langle \Delta T \rangle$) clearly have small values of $\langle \beta \rangle$, i.e. should have a fair fraction of near-circular orbits.

A similar trend between $\langle \beta \rangle$ and average time between mergings is seen in Figure 7, this time for mergers within groups of disc galaxies. Figure 8 includes all simulations and shows that, although both types of merger remnants follow a similar trend, the remnants from groups containing initially disc galaxies always have an orbital structure more biased towards near-radial orbits, as could have been expected from Figure 5.

The main purpose of the above discussion is to show that a variety of effects can influence the orbital structure of the merger remnant, such as the type of progenitors and the merging history. I did not check whether any of my merger remnants presented a reasonable fit to the galaxies observed by Romanowsky et al. (2003) and by Mendez et al. (2001), nor am I suggesting that this is the way in which ellipticals were actually formed. Presumably both pair and multiple mergers took place, in fractions which we can not yet determine. Also mergers should have occurred both between equal and between unequal mass galaxies.

To summarise, the above discussion is just one more piece of the puzzle which, together with all the rest, needs to be taken into account and could contribute to elucidating this crucial and most interesting problem.

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