N-body simulations of interacting disc galaxies

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Abstract. Disc galaxies can be substantially modified by close encounters and mergers, since their discs are very responsive components. Close interactions can be held responsible for the formation of bridges and tails, as well as for the formation of some bars, asymmetries and grand design spirals. Bound clumps can form in the tails, due to self-gravity, and could evolve to dwarf galaxies. Off-centerings and asymmetries in the central parts of barred galaxies can be made by off-centered and/or oblique impacts of sufficiently massive and compact companions. Similar impacts, but preferably centered, on non-barred galaxies can form ring galaxies. Companions on initially near-circular orbits can also cause changes to the target disc as they spiral gradually inwards. Low density companions are disrupted before reaching the center of the target and their debris form a thick disc. On the other hand most of the mass of the high density companions reaches the center, where it may form a bulge, thus entailing evolution along the Hubble sequence. Such companions thicken and expand the target disc and may also destroy bars in it. If their initial orbital plane is at an angle to the plane of the disc of the target, they can cause the latter to tilt substantially, depending on their mass and initial inclination.

1. Introduction

Galactic discs are very responsive to external forcing. Thus when a disc galaxy interacts (or merges) with another galaxy a lot of disc sub-structures can either be formed or destroyed. As examples let me mention

- bridges and tails
- spiral structure
- bars
- off-centerings / asymmetries
- rings
- warps
- lenses
- bulges
- thick discs

In this review I will be selective, neglecting some items, and developing only a few aspects of others. The choice of topic reflects to a large extent my own interests. In many cases I will focus on results obtained by the Marseille group
with our GRAPE systems. I will furthermore confine myself to purely stellar models, neglecting gas, star formation and their various consequences.

## 2. Bridges and tails

These are often seen in interacting pairs of disc galaxies and are amongst the most spectacular results of interactions. Bridges link the two galaxies, while tails extend in the opposite direction. Amongst the best known examples are the Antennae (NGC 4038/39), the Mice (NGC 4676) and the Atoms-for-Peace galaxy (NGC 7252), where the tails extend several tens of kpcs from the main bodies of the galaxies. A yet more extreme case is the Super-antennae, where the tail extent is of the order of 350 kpc (IRAS 19254-7245; Mirabel, Lutz & Maza 1991).

Toomre & Toomre (1972) convincingly demonstrated that gravity alone could account for the formation of such structures, so that there was no need to invoke magnetic or other forces. The most impressive examples are formed by direct passages, where the angular velocity of the companion is, temporarily, equal to that of some of the stars in the disc of the other galaxy. In this way there is a broad “near-resonance”, and the effect of the interaction can be strong.

Self-gravity can make further substructure in the tails. Bound clumps can form, containing both stars and gas. Such clumps could evolve to dwarf galaxies as discussed by Barnes & Hernquist (1992) and, from the observational point of view, e.g. by Schweizer (1978), by Hibbard et al. (1994) and by Duc et al. (1998). Contrary to the stars and gas, the halo material will not particularly concentrate into these clumps, so that the ratio of halo to luminous material could be quite low in dwarfs created from such clumps.

Since tails extend to large distances from the centers of their parent galaxy they could in principle be used as probes for the dark matter halo (Faber & Gallagher 1979). Dubinski, Mihos & Hernquist (1996) considered a series of galaxy models with the same disc and bulge, and halos of very different extents and masses. These models are relatively similar in their inner parts but have very different values of luminous-to-dark mass ratio. Simulations of interactions showed that the galaxies with less massive and less extended halos form longer, more massive and more striking tails than the galaxies with more massive and more extended halos. This can be easily understood since the latter galaxies will result in interactions with higher relative velocity, in which there will be fewer disc particles in near-resonance with the angular velocity of the tidal forcing. Furthermore the disc particles will need more energy to climb out of the deeper potential well. Thus Dubinski, Mihos & Hernquist (1996) set an upper limit to the halo mass in their specific model. Nevertheless one should not extrapolate this to set limits on the disc to halo mass ratio in general, since this limit can depend strongly on the distribution of matter within the two components (Barnes 1998, Springel & White 1998).

## 3. Spiral structure

A close passage of a sufficiently massive companion can form a grand design spiral in the disc of the target galaxy. The best known example, and one of the
most spectacular ones, is the spiral in M51, a galaxy interacting with its close companion NGC 5195. Statistical studies (e.g. Kormendy & Norman 1979, Elmegreen & Elmegreen 1982) have shown that M51 is not a unique case and that discs with grand design spirals very often have close companions, as noted also by Toomre & Toomre (1972), who proposed that the origin of these spirals is tidal. A large number of simulations have since shown that triggering by a close and sufficiently massive companion can indeed lead to the formation of a two armed trailing grand design spiral (e.g. Toomre 1981 and contribution to this meeting, Hernquist 1990, Howard & Byrd 1990, Sundelius 1991, Salo & Laurikainen 1993), while the physical mechanism responsible for it, swing amplification, has been presented by Toomre (1981, and contribution to this meeting).

4. Bars

Although bars could be the result of an instability of isolated galactic discs, tidal forces can trigger their formation (Noguchi 1987, Guerin, Combes & Athanassoula 1990, Noguchi 1996, Miwa & Noguchi 1998).

An interesting question in this context is whether triggered bars have the same basic properties as bars developing in isolated disc galaxies. The references mentioned above suggest that low-amplitude tidal forcing can trigger the formation of bars whose properties are largely determined by the internal structure of the target galaxy. The situation is more complicated for the case of high amplitude forcing. For such cases the work by Miwa & Noguchi (1998) suggests that the properties of the driven bars are quite different from those of bars growing spontaneously in isolated discs. More work is necessary on this very interesting point.

Bars can not only be triggered by interactions, but can also be destroyed by them (Pfenniger 1991; Athanassoula 1996b, hereafter A96b). This will be discussed in more detail in section 7.

5. Off-centerings / asymmetries

Many galaxies are at some level asymmetric and some show strong asymmetries, either in their outer regions, or in their inner parts, or in both. Typical examples are M101, the LMC, NGC 4027 etc. In some cases the center of a given component, e.g. the bar, does not coincide with that of the other components (old disc, dynamical center, etc.). The formation of such asymmetries in the outer parts can be a natural consequence of interactions. The formation of off-centerings or asymmetries in the inner parts could either be due to a mode, or be the direct result of an interaction. For example a compact and sufficiently massive companion hitting the inner parts of a barred disc galaxy can push the bar to one side. Examples of such impacts can be seen in many of my simulations and a few cases have been shown and briefly discussed by Athanassoula, Puerari & Bosma (1997, hereafter APB), Athanassoula (1996a, hereafter A96a) and A96b. All these simulations are fully self-consistent, i.e. not only the disc, but also the halo and the companion are described by particles. The bar, once displaced, sloshes around in the central part of the disc. If the galaxy is centrally concen-
trated, dynamical friction will drive the bar very fast back to the central regions and also strip it of a substantial part of its material. Using a spherical object rather than a bar, Athanassoula, Makino & Bosma (1997) tested how these processes depend on the central concentration of the target. A bar is even more vulnerable than a spherical object, since, if the passages occur at an awkward angle with respect to bar major axis, it can lose its form.

The fact that off-centered bars survive longer in less centrally concentrated galaxies than in more concentrated ones is in good agreement with the observation that such asymmetries are mainly seen in late type systems (e.g. de Vaucouleurs & Freeman 1972, Odewahn 1996). Furthermore, when the bar is pushed off-center in the simulations, a long one-armed spiral is formed (see e.g. figure 3 of A96a), very reminiscent of structures observed in late type off-centered barred galaxies such as NGC 4027 (de Vaucouleurs & Freeman 1972).

6. Ringed galaxies

Three type of rings can be found in galaxies:
- Polar rings, which are nearly perpendicular to the disc of the galaxy
- Rings in barred galaxies located at the main resonances
- Ringed galaxies

Here I will only briefly discuss the third type of rings. For the other two types see e.g. the review by Athanassoula & Bosma (1985).

Ringed galaxies can be formed from the central impact of a sufficiently massive and compact companion on a target galaxy (Lynds & Toomre 1976; Theys & Spiegel 1976; 1977, Toomre 1978). The temporary extra gravitational attraction due to this companion causes material in the target disc to move inwards. This is followed by a recoil. Thus the material in the target disc starts large epicyclic oscillations, whose period increases with distance from the center of the target. The oscillations drift out of phase and orbits crowd together and produce an expanding ring. This is a density wave propagating outwards. Often the first ring is followed by a second one and in some cases spokes form between the two. The best known example of a ring galaxy showing all these features simultaneously is the Cartwheel galaxy (A0035-324).

Several simulations have followed the first pioneering ones (e.g. Huang & Stuart 1988, Appleton & James 1990) and the results have been reviewed and discussed by Appleton & Struck-Marcell (1996). I will here only briefly present some results obtained by the Marseille group, mainly by APB. They verified that the rings are indeed density waves, as had been predicted theoretically by Lynds & Toomre (1976) and Toomre (1978). They found that the expansion velocity of the ring decreases steadily with time, both for the first and the second ring and that the first ring expands faster than the second one. The amplitude, the width, the lifetime and the expansion velocity of the first ring increase considerably with the mass of the companion. The same is true for the velocity of the particles in the ring. Rings formed by low mass encounters are more symmetric, more circular and narrower. On the other hand encounters with high mass companions increase substantially the extent of the target disc. As expected slow impacts are more efficient and form first rings of higher relative amplitude, with higher expansion velocities and longer lifetimes. The velocity of
the particles in the ring is faster for slower impacts. In general there is a broad correlation between the expansion velocity of the first ring and the mean radial velocity of the particles that constitute it at a given time. Perpendicular impacts make more symmetric and circular rings than oblique ones, which make more eccentric and broader rings. Finally such impacts make substantial changes to the vertical structure of the disc.

7. Can a companion destroy a bar without destroying the disc the bar resides in?

To answer this question I first tried simulations where the companion, initially on a rectilinear orbit, was aimed either perpendicularly, or at an angle at a barred disc galaxy. In all my trials, however, either the companion was not sufficiently massive, causing only a change in the bar pattern speed and a drop in its amplitude, or, when it was sufficiently massive, it destroyed the disc as well as the bar (APB, A96a). Discouraged by these attempts, I tried a totally different type of trajectory in which the companion started on a near-circular orbit, and I was immediately rewarded by much more success (cf. also Pfenniger 1991).

The simulations that I will discuss here were all done on the GRAPE-3 and GRAPE-4 systems in Marseille Observatory. The former, together with the available software and its performance, is discussed by Athanassoula et al. (1998). For more information on the GRAPE systems in general the reader is referred to Makino & Taiji (1998).

I made two series of simulations. In the first series there are 120 000 particles in the target galaxy, while in the second series there are 800 000 particles in the target, out of which 280 000 in the disc and the remaining in the halo. A large fraction of the simulations in the first series were run with a direct summation GRAPE code, while the remaining, as well as the simulations in the second series, were run using the GRAPE treecode. The first series consists of 46 simulations, and they include two different target galaxies (with or without bulge), three different companions and seven different orientations of the initial plane of the companion orbit. Only few simulations with companions on retrograde orbits were tried. The second series consists so far of twelve simulations, covering two different target discs, three different companions, and both direct and retrograde companion orbits. In all cases of this second series, however, the plane on the companion’s orbit coincides with the plane of the target disc. The second series, seen the number of particles used, was, to a large extent, aimed at a study of the disc thickening and, more generally, to the changes of the density and velocity distributions of the disc, the halo and the companion. In both series the mass of all particles in a given simulation is the same. Thus the ratio of masses of two components is equal to the ratio of the number of particles in these two components. Initially the halo was a Plummer sphere and the disc a Kuzmin/Toomre disc. I evolved the disc galaxy in isolation until it developed a bar and chose as initial condition for the interaction a time when the bar was well developed. In this way the companion will perturb an already barred galaxy. In other studies (e.g. Pfenniger 1991), the companion is set in the simulation before the bar has fully grown, so that the growth of the bar is partly
stimulated by the tidal force. This might cause problems with overshooting and thus complicates the analysis. In order to measure the difference I started a number of simulations in the first series with a non-barred disc, to allow comparisons between spontaneous and stimulated bars.

The three companions considered have respectively a mass equal to 1.0, 0.29, and 0.1 times that of the disc. All three have the same half mass radius and outer cut-off radius. They start on near-circular orbits somewhat outside the outer edge of the halo. Although it is quite consuming in CPU-time, such a start is necessary, in order to avoid starting the simulation out of equilibrium (as it would if the companion started within the halo) and to measure what fraction of the companion’s mass, energy and angular momentum stays in the halo.

Preliminary results from the first series of simulations are given by A96b, while the tilt of the disc plane was discussed by both A96b and Huang and Carlberg (1997). Here I will briefly present some further results, mainly from the second series of simulations.

7.1. The fate of the companion: Bulge or thick disc

The most massive companion is sufficiently dense not to be disrupted by its passage through the halo and the disc. It loses only a small percentage of its mass, while it spirals in towards the central regions of the target galaxy and most of it reaches the center. Could it thus become the bulge of the target galaxy? Before asserting this I have to examine the density and velocity distribution in the companion after the merging and compare them with those of observed bulges. The number of particles in the second series of simulations should be sufficient for this task. If these detailed comparisons confirm first impressions, then these simulations will argue that one possible way of forming a bulge is by merging a target galaxy with a sufficiently massive and compact companion. Thus such interactions, or rather mergings, would entail evolution along the Hubble sequence, since they would transform a late type galaxy with either a small bulge, or no bulge at all, to an earlier type disc galaxy, with a sizeable bulge component.

Companions of the second (intermediate mass) and third type (smallest mass) get disrupted well before reaching the center. They start losing a substantial part of their particles when they reach the main parts of the disc component. This is not done symmetrically around the surface of the companion. Most of the particles leave from the part of the companion that is farthest from the center of the target, in a tail-like fashion. This “tail” winds more and more tightly around the center of the target. The structure is less clear with time, so that, after a sufficient time has elapsed, the companion can be considered as forming a thick disk, where some structure may or may not be visible. In all cases I examined, this disc was quite thicker than the initial disc of the target galaxy. This is presumably linked to the fact that the initial diameter of the companion was in all simulations bigger than the thickness of the target disc.

7.2. The fate of the target disc

The target disc suffers considerable changes during the interaction and merger, which, as could be expected, can be seen clearest in the case of the most massive companion. Indeed the disc suffers considerable thickening, but also consider-
able extension in the radial direction. The latter can be easily understood from the conservation of angular momentum in the system, since initially the companion has substantial angular momentum because of its high mass and its large distance from the center of the target. As the target disc expands both vertically and radially, its shape stays that of a disc. An analysis of some of the simulations in the first series shows that the disc suffers some small relative thickening, i.e. that the axial ratio $c/a$ is larger after the merging than before. This needs to be confirmed with the help of the second series of simulations. Indeed these measurements are not trivial, due to the presence of the bar, which is thicker than the outer parts of the disc, due to the formation of the peanut (Combes & Sanders 1981, Combes et al. 1990, Raha et al. 1991).

The most exiting development, however, is in the case where the orbit of the companion is initially in a plane which does not coincide with that of the target’s disc, but is at an angle to it. Then the target suffers a very dramatic tilt. In simulations with the highest mass companion the plane of the target disc after the merging is close to that of the initial orbital plane of the companion. This also can be understood by angular momentum conservation. Such a plane switch has not been considered in the analytical approach of Toth & Ostriker (1992). Since it absorbs a large fraction of the vertical energy initially stored in the orbital motion of the companion, it accounts for the fact that the target disc is not overly heated in the vertical direction.

7.3. The fate of the bar

In the simulations where the companion was disrupted before reaching the center of the target, the bar suffers some evolution but is not destroyed. On the other hand in the simulations with the massive compact companion, where most of the companion reaches the target’s center, the bar does not survive the merging. In the unperturbed barred system the particles sustaining the bar rotate around the center of the galaxy in orbits elongated along the bar (i.e. orbits trapped around the $x_1$ family). When the companion approaches the bar these orbits are severely perturbed, since the mass of the companion is equal to that of the disc and therefore larger than that of the bar. These important perturbations cause the bar to be disrupted, as can be inferred by visualising the particles in the disc at sufficiently frequent intervals during the last stages of the interaction. Furthermore, after the merging is completed, the disc galaxy is much more centrally concentrated than it was at the beginning of the simulation and this can stabilise it against bar instability (A96b). The effect of central concentration on the bar instability has been discussed at length for isolated galaxies e.g. by Hasan & Norman (1990), Hasan, Pfenniger & Norman (1993), Friedli & Benz (1993), Friedli (1994) and Norman, Sellwood & Hasan (1996).

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