

Galaxy Interactions

Joshua E. Barnes

*Institute for Astronomy, University of Hawai'i, 2680 Woodlawn Drive,
Honolulu, Hawai'i, 96822, USA*

Abstract. Interacting galaxies are a natural arena for studies of *non-equilibrium* stellar dynamics, gas dynamics, and thermodynamics. Only galaxy formation itself is as deeply concerned with as many different aspects of dynamics, and the connection between interactions and the formation of galaxies is probably no coincidence. This review discusses tidal interactions, halos and orbit decay, dissipative effects in galaxy interactions, properties of merger remnants, and origins of starbursts.

1. Simulating Tidal Interactions

Why simulate interacting galaxies? First, simulations can *test theoretical ideas*. Second, detailed simulations may help in gaining *insight into real systems*. Third, simulations may *constrain galaxy parameters* such as dark halo masses.

Simulation is not a straightforward business. A dynamical model specifies the distribution function $f(\mathbf{r}, \mathbf{v})$, which depends on *six* variables. Observations, at best, yield $f(X, Y, V_Z)$, a function of just three variables: two coordinates on the plane of the sky, and a line of sight velocity. Thus simulations are underdetermined; further constraints are needed to make progress. In cosmology, one may stipulate that the observed structures grew from a linear density field $\delta\rho(\mathbf{r})/\rho$ which depends on three coordinates; this is how the “least action” method (Peebles 1994) can yield well-determined results. But in studying interacting galaxies we want to understand the *stellar* distribution, and the stars did not evolve from linear initial conditions!

So in simulating interacting galaxies, the practice has been to build equilibrium models and drop them towards each other. This approach seems to work provided that the galaxy models and their trajectories are cosmologically plausible. One example is NGC 7252, which Hibbard & Mihos (1994) simulated successfully as the result of a *direct* parabolic encounter of two disk galaxies; an earlier attempt to reproduce this system with a *retrograde* encounter (Borne & Richstone 1991) required the galaxies to start on implausibly tight circular orbits and proved inconsistent with subsequent HI observations.

1.1. Towards a model of the Antennae

The Antennae galaxies (NGC 4038/9) are fast becoming the “Rosetta stone” of interacting systems; detailed observations in almost every waveband from 21 cm to X-rays provide a remarkably complete picture of the behavior of interstellar material and star formation in the earlier stages of a galactic merger. These

galaxies have also long been a favorite of N-body experimenters. But until recently, the available line-of-sight velocity data were not good enough to support detailed simulations. New VLA observations (Hibbard, van der Hulst, & Barnes, in preparation) offer the chance to refine existing models. Goals for an improved model of the Antennae include:

1. Matching the observed velocity field. The radial velocities of the two galaxies differ by only $\sim 40 \text{ km sec}^{-1}$. To produce this, the galaxies must either be near apocenter, or falling together almost perpendicular to our line-of-sight.
2. Reconciling the adopted orbit with cosmological expectations. Simulations by Toomre & Toomre (1972) and Barnes (1988) adopted elliptical ($e \simeq 0.6$) orbits; parabolic orbits seem more plausible.
3. Reproducing the gas-rich ring in NGC 4038. This ring, clearly seen in maps of HI as well as in mid-IR (Mirabel et al. 1998), contains many luminous young star clusters (Whitmore & Schweizer 1995).
4. Explaining the “overlap region”. Recent ISO maps show this dusty region is brighter than either disk in mid-IR wavebands (eg., Mirabel et al. 1998).

Goals one and two involve adjusting the orbit, the viewing angle, and the orientations of the two disks. To rapidly explore this vast parameter space, I run “semi-consistent” simulations in which each galaxy is represented by a self-gravitating spheroid with a number of embedded test particle disks; the two disks best matching the observations are selected interactively after the calculation has run. Starting with orbits as eccentric as $e = 0.8$, this technique yields models which roughly reproduce the velocity field as well as the crossed-tail morphology of NGC 4038/9. But still less than satisfactory are the shapes of the gently curving tails and the orientations of their parenting disks; experiments are under way to study these problems and make models with parabolic initial orbits.

Goals three and four depend on gas dynamics. In high-resolution HI maps, gas in the southern tail seems to join continuously onto the ring in NGC 4038. Rings of similar size and morphology may arise as a result of gas falling back along tidal tails; the formation of such a ring is illustrated in Figure 1. Simulations of the Antennae reproducing this feature might shed some light on the conditions of star-formation in this system. Perhaps more challenging is to account for the IR-luminous overlap region. This seems to be more than just the superposition of two disks; it is probably some sort of bridge, perhaps extended along the line of sight.

1.2. Halo mass and orbit decay

Detailed simulations of systems like the Antennae may also provide useful constraints on dark halos. To produce proper tidal tails, disk material must escape to infinity. Very massive, quasi-isothermal halos prevent interacting galaxies from forming long tails (Dubinski, Mihos, & Hernquist 1996); clearly, such halos are not present around galaxies like NGC 4038/9 or NGC 7252 (Mihos, Dubinski, & Hernquist 1998). But equally massive halos with density profiles falling

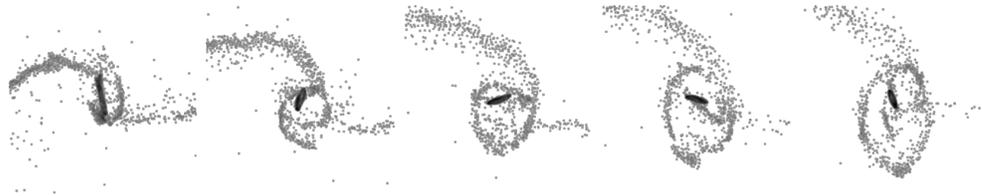


Figure 1. Formation of a gas ring by accretion of material from a tidal tail (see Barnes & Hernquist 1998, video segment 5, section 2).

off as $\rho \propto r^{-3}$ at large r are *not* excluded, as N-body experiments explicitly demonstrate (Springel & White 1998, Barnes 1999). In sum, tail length tells us something about the structure of halos, but little about their total mass.

However, it seems unlikely that arbitrary amounts of dark mass can be included in simulations of interacting systems. The orbital evolution of a pair of galaxies is largely governed by the interaction of their dark halos (White 1978, Barnes 1988). Too much or too little orbital decay will hinder the construction of models which evolve from plausible initial conditions to configurations matching the observed morphologies and velocity fields of real systems. Possible indicators of halo mass in interacting systems include:

1. Tail kinematics; the run of velocities along a tidal tail may constrain the potential.
2. Tail fallback; if orbit decay is strong, returning tail material may miss the disk by a wide margin.
3. Galaxy velocities; do the hulks preserve their original sense of motion about each other?

The last of these, in particular, seems relevant to NGC 4038/9; the galaxies must retain a good deal of their orbital angular momentum to produce the crossed tails emblematic of this system.

2. Dissipation and Thermodynamics

Unlike stars, gas responds to pressure forces as well as gravity; moreover, gas flows develop shocks whereas streams of stars freely interpenetrate. Even without the complications of star formation, the dynamics of gas in interacting galaxies is a difficult problem. But dissipative dynamical systems generally possess *attractors*; in the long run, most trajectories are captured by one attractor or another. Consequently, gas in interacting galaxies tends to end up in a few stereotypical structures.

The thermodynamic history of the gas is probably the factor which determines its fate. To date, most simulations treat gas thermodynamics rather crudely; the cooling function is cut off at $T_c = 10^4$ K to prevent the gas from “curdling”, and the resulting behavior is basically that of an isothermal fluid

with $T = T_c$ (Barnes & Hernquist 1996, hereafter BH96). Improving on the present treatments may require including star formation and feedback; one possible approach to this difficult problem is described in § 4. The rest of this section reviews results obtained with and without cooling in an attempt to anticipate the results of more realistic experiments.

Work by several investigators confirms that tidal perturbations of gas-rich disk galaxies result in rapid gas inflows (Icke 1985, Noguchi 1988, Hernquist 1989, Barnes & Hernquist 1991). The immediate physical cause of these rapid inflows is a systematic transfer of angular momentum from the gas to the disk stars; tidally perturbed disks develop bars (or other non-axisymmetric structures) which exert gravitational torques on the gas (Combes, Dupraz, & Gerin 1990, Barnes & Hernquist 1991). Such inflows require strong shocks and rapid cooling, which work together to drive the gas irreversibly toward the center of the potential. As a perturbed disk settles down the gas often converges onto kpc-scale closed orbits aligned with the stellar bar (BH96).

Dissipative mergers between disk galaxies lead to further inflows, with large amounts of gas collecting in ~ 0.2 kpc-scale clouds (Negroponte & White 1983, Barnes & Hernquist 1991). These nuclear clouds contain material driven in toward the centers of galaxies by earlier tidal interactions; during the final merger, the gas again loses angular momentum to the surrounding material. It seems likely that the same physical mechanism lies behind the inflows in perturbed disks and in merger remnants; in both cases the entropy of the system grows as gas falls inwards.

A different fate awaits the gas which does not suffer strong shocks and subsequent cooling in the early stages of an encounter. This material does not participate in rapid inflows, and retains much of its initial angular momentum. Consequently, it tends to collect in an extended, rotationally supported rings or disks; one such example has already been presented in Figure 1. In merger remnants, such disks may be strongly warped by gas falling back from tidal tails (BH96). Early-type galaxies with warped gas disks include NGC 4753 (Steiman-Cameron, Kormendy, & Durisen 1992) and NGC 5128 (van Gorkom et al. 1990); though these disks are usually attributed to accretions of gas-rich satellite galaxies, some may actually result from major mergers.

The two outcomes just described – nuclear clouds or extended disks – seem to be the only real attractors available to dissipative gas in merger simulations. However, if the gas fails to cool then another outcome is likely – a pressure-supported atmosphere about as extended as the stellar distribution (BH96). Though most phases of the ISM cool efficiently, initially hot gas ($T \gtrsim 10^5$ K, $n \lesssim 10^{-3}$ cm $^{-3}$) could be shock-heated during a merger and might produce envelopes of X-ray gas like those found around some elliptical galaxies. On the other hand, X-ray observations of the Antennae (Read, Ponman, & Wolstencroft 1995) and Arp 220 (Heckman et al. 1996) reveal apparent *outflows* of up to $10^9 M_\odot$ of hot gas. The properties of these outflows are inconsistent with shock-heating and seem to require significant injections of mass and energy from merger-induced starbursts.

3. Structure of Merger Remnants

Much of this meeting has focused on possible ways in which nuclear mass concentrations – such as steep central cusps or black holes – influence the global structure of elliptical galaxies. This discussion is motivated by the apparent dichotomy (Kormendy, these proceedings) between faint ellipticals (which have steep central profiles, “disky” isophotes, and rapid rotation) and bright ellipticals (which have shallow central profiles, “boxy” isophotes, and slow rotation). But other factors besides central density profile can influence galaxy structure.

3.1. Unequal-mass mergers

Rapidly-rotating systems may result when a large disk galaxy merges with a smaller companion, as illustrated in a modest survey of unequal-mass encounters (Barnes 1998). In these experiments, both galaxies contained bulges, disks, and halos; the larger galaxy had 3 times the mass of the smaller, and rotated ~ 1.32 times faster. The galaxies were launched on initially parabolic orbits and went through several passages before merging; remnants were evolved for several more dynamical times before being analyzed.

Figure 2 shows edge-on views and velocity distributions for an unequal-mass merger remnant. Unlike the products of equal-mass mergers (Barnes 1992), this object is fairly oblate, with axial ratios $b/a \simeq 0.9$, $c/a \simeq 0.6$. A good deal of “fine structure” is still present due to incomplete phase-mixing, but the edge-on views show a distinctly disk-like morphology. The velocity profiles, which mimic the result of placing a narrow slit along the remnant’s major axis, show that this object is rapidly rotating; in fact, $v/\sigma \gtrsim 2$ or more at larger radii. And as the cyclic version of the velocity plot makes clear, the line profiles are asymmetric,

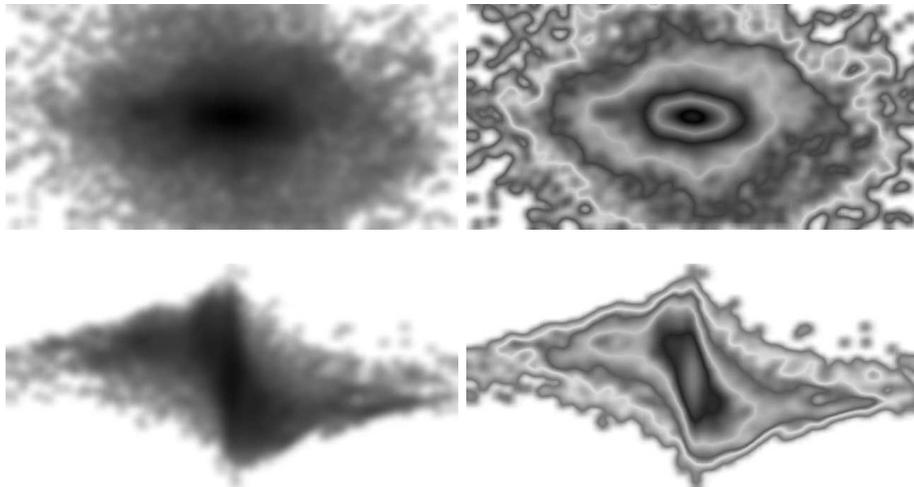


Figure 2. Remnant produced by an unequal-mass merger. Top: edge-on views. Bottom: line-of-sight velocities versus major axis position. Left: natural grey scale. Right: cyclic grey scale.

rising sharply on the leading side of the peak, but falling off gradually on the trailing side.

The initial conditions used for this experiment were fairly generic; the larger disk was inclined by $i = 71^\circ$ with respect to the orbital plane, the smaller disk by $i = 109^\circ$. Between half and three-quarters of a small sample of unequal-mass merger remnants exhibit the rapid rotation and asymmetric line profiles seen in this example (Bendo & Barnes, in preparation). These objects clearly don't resemble bright ellipticals, but do seem fairly similar to faint ellipticals or S0 galaxies. The morphological and kinematic features which support this classification are due to the incomplete scrambling of galactic *disks* in unequal-mass mergers. If dissipative collapse is responsible for the rapid rotation of faint ellipticals (Kormendy 1989), a subsequent merger may still be needed to *transform* the resulting object into something resembling an early-type galaxy.

3.2. Dissipative mergers

By producing inflows, dissipation can dramatically deepen galactic potential wells, and these deeper wells seem to influence the dynamics of collisionless material (eg., Katz & Gunn 1991, Udry 1993, Dubinski 1994, BH96). But these studies mostly examined effects of dissipation on dark halos; only the last one focused on disk-galaxy mergers, and that work compared but one pair of carefully-matched simulations.

The two remnants compared by BH96 were produced by mergers of equal-mass bulge/disk/halo galaxies. Both experiments started with *exactly* the same initial conditions, using disk inclinations of 0° and 71° ; both were evolved with the same spatial resolution (a.k.a. “force softening”). In the dissipative version, a tenth of the disk mass was treated as gas with a cooling cut-off at $T_c = 10^4$ K, while in the collisionless version everything obeyed the collisionless Boltzmann equation.

Figure 3 compares the ellipticity profiles of these two remnants. Beyond their half-light radii ($r_{\text{hl}} \simeq 0.18$ model units) both remnants are nearly oblate and rotate rapidly in memory of the direct ($i = 0^\circ$) disks used in the initial conditions. But inside r_{hl} the two remnants are quite different; the collisionless

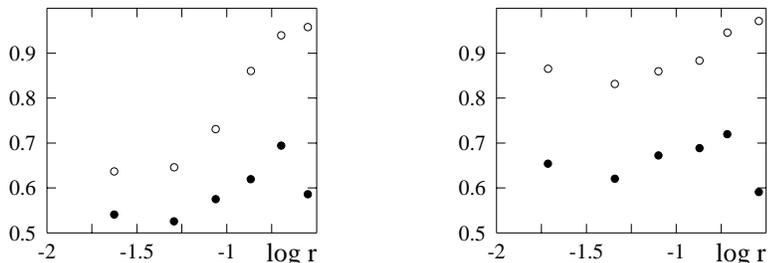


Figure 3. Ellipticity profiles for collisionless (left) and dissipative (right) versions of the same merger remnant. Open circles represent b/a , filled circles c/a .

version is a triaxial ellipsoid rapidly tumbling about its minor axis, while the dissipative version is fairly oblate and slowly rotating.

How does dissipation influence the shape of merger remnants? The dissipative remnant has a deeper potential well as a result of its central gas cloud, which contains $\sim 4.5\%$ of the luminous mass, or $\sim 0.9\%$ of the total. But the finite resolution of the force calculation spreads this central mass over a radius of $\sim 0.04 r_{\text{hl}}$; thus compared to a black hole or singular logarithmic potential, this mass may be ineffective at scattering box orbits (Valluri, these proceedings). Moreover, the oblate shape of the remnant seems to be established at the moment of the merger itself instead of developing progressively from the inside out (Ryden, these proceedings).

Thinking that the shapes of these remnants might be constrained by the scarcity of box orbits, I constructed a composite mass model with the density profile of the dissipational remnant and the ellipticity profile of its collisionless counterpart, and used its potential to evaluate the phase-space volumes of the major orbit families (Barnes 1998). While this composite offered fewer boxes and more z-tubes than the collisionless remnant, bona-fide box orbits were present at all binding energies. Thus self-consistent equilibria as centrally concentrated as the dissipational remnant and as flattened as the collisionless remnant may exist. However, some finesse is probably required to realize such equilibria. Merging sows stars far and wide across phase space; not all physically consistent systems may be constructed with such a blunt instrument.

All of this work is based on only one pair of simulations, and the two remnants compared by BH96 may not be entirely typical. For example, the pre-merger disks in these experiments developed bars, and the bars in the dissipational version had significantly higher pattern speeds. Thus when the disks merged, their bars had different orientations, and this might influence remnant structure. Comparison of a larger sample of collisionless and dissipative merger remnants is clearly warranted, but sufficient computer power is hard to find. Meanwhile, collisionless mergers between models of various central concentrations may help expose the connection between density profile and remnant shape (Fulton & Barnes, in preparation).

4. Simulations of Starburst Galaxies

The crude treatment of gas thermodynamics in most work to date is perhaps the greatest barrier to simulating star formation in interacting galaxies. As described in § 2, radiative cooling is typically cut off at 10^4 K, and most of the gas remains close to this temperature. Stars, on the other hand, form at much lower temperatures; consequently, sites of star formation can't be directly located in the simulated gas.

Within the framework of most simulations, gas density is the only variable with an interesting range of values, so most treatments assume the star formation rate is a function of the gas density. This approach has some justification; studies of star formation in systems ranging from quiescent disk galaxies to violent starbursts find that star formation rates roughly follow a Schmidt (1959) law of the form $\dot{\Sigma}_s \propto \Sigma_g^n$, where Σ_s and Σ_g are the stellar and gaseous surface densities, respectively, and the index $n \simeq 1.4 \pm 0.15$ (eg., Kennicutt 1998). The

usual approach is thus to adopt a star formation law of the form $\dot{\rho}_s \propto \rho_g^n$, where ρ_s and ρ_g are the stellar and gaseous volume densities, respectively.

The implementation of feedback effects due to stellar evolution and supernovae is particularly difficult. Cooling is so rapid that the otherwise plausible strategy of dumping thermal energy into the gas proves ineffective; the energy is radiated away before anything else can happen (Katz 1992, Summers 1993). Another trick is to impart some outward momentum to gas particles surrounding sites of star formation and/or supernovae; this seems more effective, but involves an arbitrary efficiency factor (Navarro & White 1993, Mihos & Hernquist 1994). It's unlikely that feedback can be properly implemented as long as the gas is effectively treated as a single-phase medium.

A promising alternative to density-driven star formation is now available (Gerritsen & Icke 1997). In this approach the gas is allowed to cool below 10^4 K, and sites of star formation are defined by a Jeans criterion. The stellar radiation field, calculated in the optically thin limit, is used to heat the gas. Star formation is thus a self-regulating process; negative feedback maintains the system in a quasi-stable state while slowly converting gas to stars. Competition between radiative heating and cooling creates a two-phase medium with temperatures of 10^2 K and 10^4 K; a third phase at 10^6 K appears when the effects of supernovae are included. As a bonus, the resulting star formation obeys a Schmidt law with index $n \simeq 1.3$.

It may turn out that many of the desirable features of this approach are simple consequences of combining radiative cooling and negative feedback. Some details surely require modification; the treatment of the radiation field seems particularly suspect since galactic disks, edge-on, are not optically thin. But the general view of star formation as a self-regulating process and the re-introduction of gas temperature as a physically interesting variable are surely major improvements on previous treatments.

Does the treatment of star formation make a real difference in the outcome of simulations? In at least one respect, it does. Simulations using the Schmidt law predict that interacting late-type disk galaxies consume most of their gas shortly after their first passage; merger-induced starbursts only result if the disks are protected from bar formation by compact central bulges (Mihos & Hernquist 1996). In contrast, simulations using self-regulated star formation predict that bulgeless disk galaxies retain enough gas to fuel ultra-luminous starbursts during their final mergers; while star formation rates increase after the first passage, radiative heating delays violent star formation until the merger drives most of the gas into a compact central cloud (Gerritsen 1997).

To date, outflows like those seen in interacting starburst galaxies have not been reproduced with either treatment of merger-induced star formation. This remains an important challenge for the future.

5. Discussion

Within the space of this brief review, it's impossible to do more than touch on a few aspects of galaxy interactions; I've said nothing about the tidal genesis of grand-design spirals, origins of ring galaxies, multiple mergers and the formation

of cD galaxies, or interactions in groups and clusters, to name a few. The main points I have tried to address are listed here:

1. Simulating interacting galaxies is an *art*; it can't be reduced to a recipe. Picasso defined art as "a lie which makes us realize truth", and this seems to be a good stance to adopt when trying to reproduce real galaxies. Some features of the Antennae may be clues leading to fundamental insights, while others may be due to quirks of the pre-encounter disks. We don't always know which is which; experience is the only guide.

2. In interacting galaxies, thermodynamics is the key to the fate of the gas. Gas which encounters strong radiative shocks in the early phases of a collision will diverge from the stars and fall into the centers of interacting galaxies and merger remnants. Gas which does not suffer such shocks until the later stages of a collision, on the other hand, retains much of its initial angular momentum and builds up extended disks.

3. Remnant structure is determined by many factors. Steep central cusps (or nuclear black holes) may suppress strong triaxiality, but this doesn't explain why galaxies with such profiles rotate rapidly. More generally, sheer *existence* of self-consistent equilibria is not enough to explain the properties of elliptical galaxies; the details of formation play an important role.

4. Simulations including star formation are still in their early days; a good deal of further work is needed to develop and test alternate approaches. Plausible treatments of feedback from star formation and evolution require abandoning the assumptions which effectively limit the simulated gas to a single phase.

As noted in the abstract, galaxy mergers have deep connections to galaxy formation. For example, the issues reviewed in § 2 and 4 arise in cosmological simulations of disk galaxy formation; in dissipative CDM simulations, gas inflows are so efficient that little remains to build disks (Navarro & Benz 1991, Navarro & White 1994, Navarro & Steinmetz 1997). The resolution of this problem is probably to implement strong feedback of the kind long assumed in hierarchical models of galaxy formation (White & Rees 1978, White & Frenk 1991, Kauffmann, White, & Guiderdoni 1993, Navarro, Frenk, & White 1995). This may well be the same sort of feedback needed to reproduce the outflows of hot gas in violently interacting starburst galaxies.

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