DYNAMICS OF MERGERS & REMNANTS

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Abstract. This review focus on some issues which seem relevant to recent discussions: (1) how halo structure influences tail length, (2) the fate of power-law density cusps, (3) the results of unequal-mass disk galaxy mergers, and (4) the behavior of hot and cold gas in merging disk galaxies.

1. Halos & Tail Length

The tails of interacting disk galaxies were lucidly explained by Toomre & Toomre (1972). Briefly, tails develop when tidal forces tear galactic disks apart; material on the side of the disk furthest from the companion galaxy, suddenly free of the gravitational pull which had kept it in a circular orbit, escapes along a nearly linear trajectory and so produces an ever-lengthening tail. Self-consistent simulations of galaxies possessing modest dark halos have elaborated but not fundamentally modified this basic picture (Negroponte & White 1982, Barnes 1988). A recent study claims that the long tidal tails observed in many interacting systems can't escape from dark halos if these halos have more than about ten times the luminous mass (Dubinski, Mihos, & Hernquist 1996). But this claim is model-dependent, as shown by the experiments described below.

In these experiments, each galaxy models had three components: a bulge, a disk, and a halo. The bulges were Hernquist (1990) models with mass[1] $M_{\rm b} = 0.0625$ and scale radius 0.04168; beyond a radius of 4.0 the bulge density tapered away smoothly. The disks were exponentials, with mass $M_{\rm d} = 0.1875$, radial scale length $\alpha^{-1} = 1/12$, and vertical scale height $z_0 = 0.005$. The halos were based on the Navarro, Frenk, & White (1996; hereafter NFW) model, which has a logarithmically divergent mass.

[1]Unless otherwise noted, results are quoted in arbitrary units with $G = 1$.

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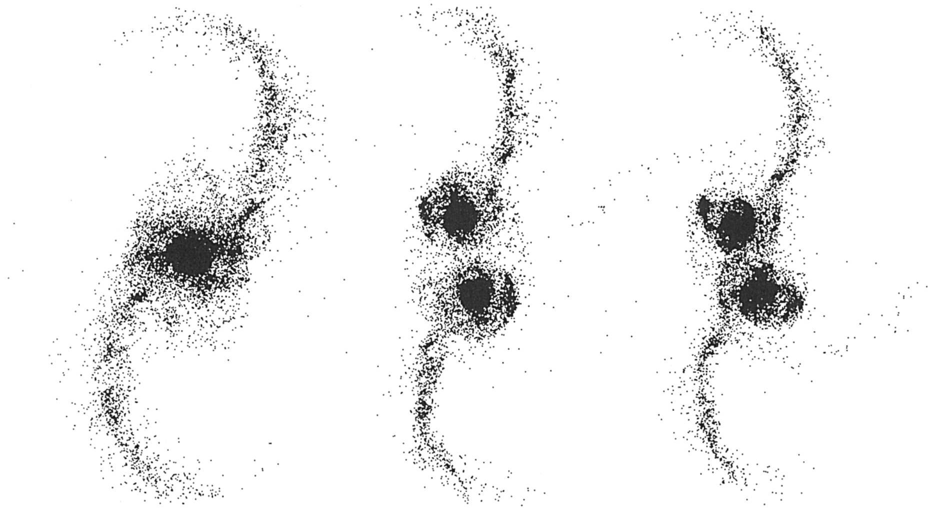

Figure 1. Tails produced by parabolic encounters with halo-to-luminous mass ratios of 5:1 (left), 10:1 (middle), and 20:1 (right).

To obtain finite total masses the NFW halo profiles were tapered:

$$\rho(r) = \begin{cases} \dfrac{M_{\rm a}}{\log(2) - 0.5} \, \dfrac{1}{4\pi r(a+r)^2} & \text{if } r < b \ , \\ \rho_{\rm b}(b/r)^2 \exp[-\gamma((r/b)^2 - 1)] & \text{otherwise} \ , \end{cases} \tag{1}$$

where $M_{\rm a}$ is the mass within the halo scale radius a and the parameters $\rho_{\rm b}$ and γ were chosen so that both $\rho(r)$ and its first derivative are continuous at $r = b$. All the models used halo mass and length scales $M_{\rm a} = 0.2$ and $a = 0.2$; the taper radius b was used to adjust the total halo mass $M_{\rm h}$ as follows:

$$\begin{array}{cccc} b & 0.55285 & 2.8099 & 34.95 \\ M_{\rm h} & 1.25 & 2.50 & 5.00 \end{array} \tag{2}$$

Combining these halos with the standard bulge and disk yielded composite models with luminous-to-dark ratios of 1:5, 1:10, and 1:20, respectively. All these models had identical, fairly flat rotation curves out to at least six disk scale lengths.

All calculations started with the two galaxies only 5 length units apart; thus the low-mass halos were initially well-separated while the others significantly overlapped. The potential energy of each initial configuration was used to assign the galaxies relative speeds consistent with asymptotically parabolic orbits; the directions of the initial velocities were set so as to obtain pericentric separations of about 0.2 length units in each case. As shown in Figure 1, all three experiments produced acceptable tails.

The success of this tail-making exercise is hardly unexpected. To make a proper tail, the velocity of the tail material must exceed the local escape velocity. The NFW model, with $\rho \propto r^{-3}$ at large radii, has a *finite* escape velocity even though its total mass diverges; consequently it is possible to obtain proper tails with encounters involving arbitrarily massive halos. The models used by Dubinski et al., on the other hand, have potential wells which become significantly deeper as total halo mass increases. *Long tails constrain potential well depth, but not halo mass itself.*

2. Cusp Survival

Especially since the refurbishment of *HST* it's become clear that few if any early-type galaxies have constant-density cores; instead, the luminosity profiles of some galaxies are power-laws, while others show a break and a more gradual rise to the innermost point (eg. Faber et al. 1997). Core profile shape is correlated with luminosity; bright Es have breaks, while faint ones have power-laws. It is natural to ask what merging will do to this dichotomy. A simple argument outlined below suggests that merging preserves steep power-law cusps.

Pressure-supported systems may be approximately described by isotropic distribution functions of the form $f \simeq f(E)$; in such systems, most of the variance of the actual DF is due to its variance with binding energy E. Systems with central cusps have singular distribution functions with formally infinite phase-space densities; for example, a density profile $\rho \propto r^{-2}$ implies that the amount of mass with phase-space densities above f scales as $M(> f) \propto f^{-1/2}$. When systems merge, violent relaxation (Lynden-Bell 1967) spreads material over a range of binding energies; subsequently, phase mixing averages phase-space density on surfaces of constant E. But this violent relaxation is *incomplete*; numerical studies of mergers show that potential fluctuations die down before binding energies are completely randomized (e.g. White 1987). So phase mixing can only average over a limited range of fine-grained phase-space densities. The final coarse-grained DF, which describes the remnant at later times, is thus similar to the initial DF; in particular, the DFs of remnants produced by mergers of galaxies with cusps should still be singular after "the dust settles".

Merger simulations indicate that neglect of velocity anisotropy does not badly compromise this argument. The experiments reported here involved parabolic collisions between identical "gamma" models (Dehnen 1993; Tremaine et al. 1994), with inner density power-law slopes of $\gamma = 1$, 1.5, and 2; each model had total mass $M = 1$ and half-mass radius $r_{1/2} =$ 0.25. These simulations used $N = 65536$ bodies, advanced with a leap-frog time-step of $\Delta t = 1/512$; the smoothing scale in the force calculation was

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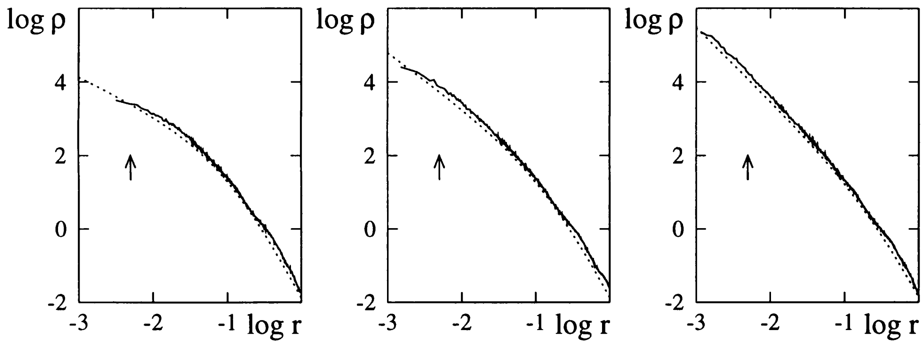

Figure 2. Spherically-averaged density profiles of merger remnants (solid lines) compared with initial models (dotted lines). Results are shown for initial models with $\gamma = 1$ (left), 1.5 (middle), and 2 (right). The arrow in each plot indicates the smoothing length.

0.005. The models were launched on asymptotically parabolic orbits which reached a pericentric separation of $r_{\rm p} = 0.25$ at time $t = 1$; by time $t = 8$ the systems had merged and largely relaxed. Figure 2 compares the density profile of each remnant with the gamma model of its progenitors. As in earlier studies (eg. White 1978; Villumsen 1983), remnant density profiles are closely related to those of the initial systems. Shown here more clearly than before is that steep power-law cusps survive merging.

Such results have implications for dark halos (e.g. NFW, Fukushige & Makino 1997) as well as for visible galaxies. One implication for galaxies is that *mergers can't transform the power-law profiles of faint Es into the broken profiles of bright Es unless violent relaxation is somehow prolonged*, perhaps by the effects of a pair of massive black holes (e.g. Makino & Ebisuzaki 1996, Quinlan & Hernquist 1997). If broken profiles are produced by inspiraling black holes, the central regions of bright Es should be effectively homogenized, with little velocity anisotropy and relatively weak color and metallicity gradients.

3. Disk Destruction

Galactic disks are fragile; while accretions of low-mass satellites do little harm mergers with comparable objects "scramble" disk galaxies into hot spheroids. Between these extremes, disks may be damaged but not altogether obliterated (eg. Walker, Mihos, & Hernquist 1996). Clustering models suggest that typical mergers involve objects with broadly distributed mass ratios; a ratio of 3:1 seems typical. What happens to a disk galaxy which merges with a companion one-third as massive?

A partial answer to this question emerges from a modest survey of

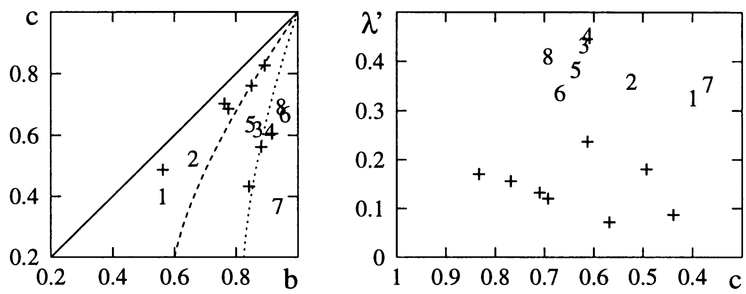

Figure 3. Remnants of 3:1 mergers, numbered 1 to 8, compared with remnants of 1:1 mergers, indicated by crosses. (Left) axial ratios: b and c are the intermediate and minor axis ratios, respectively. (Right) rotation *vs.* minor axis ratio: λ' is a dimensionless measure of angular momentum (Barnes 1992), equal to unity for a pure, co-rotating disk.

unequal-mass encounters (Barnes 1998). In these experiments, both galaxies were bulge/disk/halo systems; the larger galaxy had 3 times the mass of the smaller, and rotated $\sqrt[4]{3}$ times faster in accord with the Tully-Fisher relationship. 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 3 compares the shapes and kinematics of the 3:1-mass remnants with a companion sample of 1:1 remnants. The plot on the left shows axial ratios, computed from the moment of inertia of the more tightly-bound half of the luminous material in each remnant. As a group, the 3:1 remnants are fairly oblate, while the 1:1 remnants are more triaxial. The plot on the right shows angular momentum content plotted against minor axis ratio; the 1:1 remnants, which are flattened by velocity anisotropy, rotate at less than half the typical rate of the 3:1 remnants. On the whole, the 3:1 remnants are dynamically unlike their equal-mass counterparts.

What Hubble type would these objects be assigned? Of the eight cases reported here, numbers 3, 4, 5, 6, & 8 are fairly oblate and rapidly rotating. Moreover, many stellar orbits in these remnants are roughly circular; at any given energy, most of the minor-axis tube orbits have nearly the maximum possible angular momentum. Finally, several of these remnants actually look disk-like when viewed edge-on. Apparently, *some 3:1-mass merger remnants are more like S0 galaxies than ellipticals.*

Some early-type disk galaxies may thus owe their relatively hot disks and massive spheroids to unequal-mass mergers (Schweizer, this volume). If unequal-mass mergers are as common as cosmological models indicate, they could form a large fraction of S0 galaxies.

4. Hot & Cold Gas

Interstellar material, though only a modest part of the total mass, plays a profound role in disk galaxy mergers: it reveals the large-scale kinematics of tidal features (Hibbard et al. 1994), powers starbursts in luminous IR galaxies (Sanders & Mirabel 1996), and builds dense central regions in early-type merger remnants (Schweizer 1990, Kormendy & Sanders 1992). The complex behavior of interstellar gas is incompletely captured by the present generation of numerical experiments. Most simulations have in effect modeled the gas isothermally (Barnes & Hernquist 1996, and references therein); this rather drastic simplification tends to obscure the relationship between the thermal history and dynamical behavior of gas in interacting galaxies.

Color plate 4 (p. xxii) presents a simulation which gives some indication of the dynamics of a multi-phase medium in a merger of equal-mass disk galaxies. On the left are the stars, which evolved collisionlessly. In the middle is "hot" gas, assumed to be too tenuous to cool on dynamical timescales. On the right is "cool" gas with $T \simeq 10^4\,\mathrm{K}$, which serves as a proxy for molecular and atomic interstellar material.

The bulk of the hot component roughly followed the stellar distribution throughout the calculation. A small amount was heated above $10^6\,\mathrm{K}$ during the first interpenetrating passage of the two disks, but most of the gas warmed up only *after* this passage. When the tidally disturbed disks formed bars, the resulting noncircular motions caused shocks which heated the gas to several $10^5\,\mathrm{K}$. The final encounter of the two disks heated the gas to the virial temperature, forming a pressure-supported atmosphere about as extended as the stellar component (Barnes & Hernquist 1996). In contrast, *ROSAT* observations of the Antennae (Read et al. 1995) and other starburst systems show actual outflows of gas at $\sim 10^6\,\mathrm{K}$; energy sources associated with ongoing starburst probably power these outflows.

Gas which cools only in the later stages of an encounter retains much of its initial angular momentum. Unless strong shocks develop during violent relaxation, this gas can't become radically segregated from collisionless stuff; if it dissipates after the remnant's potential settles down, it form a disk rotating in the same direction as the stellar remnant. Gradual return of gas from tidal tails (eg. Hibbard & van Gorkom 1996) can build up disks with radii of many kpc. Since the returning gas generally falls in at an angle to the principal planes of the remnant, such disks are likely to be warped.

Infall of material from tidal tails may have interesting consequences even before the galaxies actually merge. In the right-hand column, third frame from the top, a ring of gas is seen around the more face-on galaxy. A video shows that this ring formed from gas returning from the tidal tail extending to the left of this disk (Barnes & Hernquist 1998). This case was particularly favorable since the disk lay in the orbital plane, but the other disk in this simulation, though inclined by 71°, also developed a ring. The extended ring of molecular gas and star formation in the northern disk of Antennae (Color plate 5, p. xxiii) may likewise have resulted from material returning from the gas-rich southern tail; tests of this idea await more detailed analysis and dynamical modeling of this system.

Dissipation at early stages of galactic encounters has the effect of driving gas inward to pool within the central kpc of interacting disks (Icke 1985, Noguchi 1988) and at radii an order of magnitude smaller in merger remnants (Negroponte & White 1982, Barnes & Hernquist 1991). This material must lose *most* of its angular momentum to become so concentrated, and gravitational interaction with collisionless material seems to be the crucial brake on the rotation of the gas. What little angular momentum the gas retains may be poorly correlated with the angular momentum of the rest of the remnant, giving rise to kinematically decoupled central structures (Hernquist & Barnes 1991).

Still missing from these experiments is a proper treatment of interactions between various phases of the interstellar material. Simulations with star formation and stellar evolution are needed to incorporate "feedback" effects; one promising approach to this problem is described by Gerritsen & Icke (this volume). Hot gas can ionize neutral material as it falls back from the tidal tails; this may explain the lack of HI in the bodies of merger remnants like NGC 7252 (Hibbard et al. 1994). If the pressure of the hot gas is high enough, it may implode molecular clouds, triggering galaxy-wide starbursts (Jog, this volume); the extensive star formation in the Antennae could have been triggered in this fashion. Finally, the ram pressure of the hot gas may impart significant momentum to cooler interstellar material, thereby explaining the rather curious offsets between stellar and gaseous tails observed in some interacting systems (Schiminovich et al. 1995, Hibbard & van Gorkom 1996, Hibbard & Yun 1998).

Thus, the new data from multi-wavelength studies of systems like the Antennae offer a strong motivation for numerical simulations incorporating both hot and cool interstellar gas. Such simulations are needed to interpret the observations and to test theories of galactic transformation via violent interactions and mergers. Some questions which might be answered in this way include: What's going on in the "overlap" region of the Antennae; is this an interpenetrating encounter of two gas-rich systems? Did overpressure of hot gas trigger the *galaxy-wide* starbursts seen in this system? Will the resulting stars and star clusters spread throughout the remnant or concentrate in its central regions? Do systems like the Antennae give rise to ultraluminous IR galaxies like Arp 220? What powers the outflows of X-ray gas in the Antennae and in ULIR galaxies? Can such winds clean out the dusty central regions of ULIR galaxies, possibly exposing central AGNs? What happens to the outflowing gas; how much is returned to the intergalactic medium, and how much eventually falls back?

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