SIMULATIONS OF GALAXY MERGERS

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ABSTRACT The last few years have seen a considerable amount of effort devoted to the problem of simulating the coalescence of galaxies. After a discussion of the merits and limitations of the N-body techniques that have been used, I summarise the insight this research gives into the mechanisms driving strong interactions in galaxy collisions and into the structure of the remnants such collisions produce.

1 INTRODUCTION

Strongly interacting pairs of galaxies have been known for many years, but Toomre & Toomre (1972; hereafter TT) were the first people to emphasise that such systems are likely to degenerate rather rapidly into single ellipsoidal star piles, suggesting that at least some elliptical galaxies formed by the merger of pre-existing spirals. Galaxy mergers also came into prominence in at least two other contexts during the 1970's. Lecar (1975), Ostriker & Tremaine (1975) and White (1976) independently noted that dynamical friction would cause bright galaxies to collect at the centre of rich galaxy clusters, and that these galaxies might coalesce to form the supergiant cD's often oberved there. Ostriker & Tremaine (1975) and Tremaine (1976) considered how an analogous process would cause satellite galaxies to merge with their parents. Aspects of all these processes are discussed in the reviews by Toomre (1977), Tremaine (1981) and White (1982). Little progress can be made on the problem of galaxy coalescence by analytic methods. However, the recent rapid increase in available computing power and the development of efficient N-body programs have made it possible to simulate the interaction and merging of galaxies directly; as a result considerable effort has been put into merger simulations over the last five years. While the problem is still far from fully explored (for example there are few published simulations of mergers of unequal systems) a number of general results are beginning to emerge.

2 NUMERICAL METHODS

The collision and merging of galaxies is difficult to simulate

E. Athanassoula (ed.), Internal Kinematics and Dynamics of Galaxies, 337–345.

realistically with present techniques. During galaxy merging large global changes in structure occur and can only be followed correctly by a program which solves self-consistently for the gravitational field at all times. In all but a few atypical situations the mass distribution is fully three-dimensional and possesses no usable symmetry properties. In addition the program must have a large dynamic range. A resolution of a few hundred parsecs is needed to model the central regions of a galaxy, while the orbit of a pair prior to collision should be several hundred times bigger. The orbital period of stars in a galaxy core is shorter than the time required for complete merging by a similar factor. The ideal simulation method should thus have temporal and spatial resolution which can vary strongly with particle position.

The simplest kind of N-body scheme is a direct integrator which calculates the force on each particle by summing the forces exerted on it by all other particles. The most efficient such schemes use two timesteps for each particle; one for the rapidly changing force due to a few nearby particles and one for the more slowly changing force due to the rest of the system (Ahmad & Cohen 1973). Such codes are clearly Lagrangian. Their resolution limit is a fraction 1/N of the mass of the system. Their spatial and temporal resolution vary with position so that the orbits of a random sample of stars are followed with uniform accuracy. These properties are ideal for the merger problem, but the time-consuming force calculation limits the number of particles to $N \lesssim 10^3$. As a result, the fluctuating force field due to particle discreteness is much more important in such a simulation than in a real galaxy. Discreteness effects can be partially overcome by softening the interaction potential on small scales. This amounts to replacing the particles by fuzzy blobs of finite size; the price paid is the introduction of a resolution limit given by the softening length. When using such a code to simulate hot ellipsoidal systems (as in the merger simulations of White 1978, 1979, and Roos & Norman 1979) the effects of discreteness are limited to an orbital diffusion which drives a gradual change in structure. Galaxies with a cold disk component are much harder to simulate and severe disk instabilities can only be suppressed by using a large softening length, a careful setup technique and a stabilizing hot spheroidal component. Attempts to make "spiral" galaxies for use in merger experiments have met with considerable difficulty (Gerhard 1981, Farouki & Shapiro 1982, Quinn 1982, Negroponte 1982).

Transform methods can speed up the force calculation considerably. The simplest technique is to tabulate a smoothed particle density on a cubic grid and then use Fast Fourier Transforms to obtain the potential. Miller & Smith (1980, this conference) have used such a method to follow 10^5 particles on a 64x64x64 grid. Such a large calculation completely suppresses all discreteness problems and allows a very detailed sampling of phase-space. Unfortunately, the method has linear resolution independent of position and requires an equal timestep for all particles. When applied to merger simulations it is actually less able to model centrally concentrated galaxies and has more difficulty in following a merger to completion than the direct codes discussed above. More efficient transform codes can be constructed using spherical harmonic expansions centred on each galaxy; the radial gridding can then be designed to provide greatly improved resolution in regions where it is needed. Such codes are difficult to implement because two grids are needed whose centres are accelerated with respect to each other and to an inertial frame. Impressive results from a two-dimensional code of this type have been published by van Albada & van Gorkom (1977). A technique which is fully Lagrangian and avoids all gridding has been introduced by Villumsen (1982). The force field within a galaxy is calculated using the first few terms of a tesseral harmonic expansion of the potential of each particle about the galactic centre. The acceleration of the particles can be computed by ordering them in radius and looping through them twice. In principle the resolution of this technique is limited only by the number of particles, although Villumsen found it useful to introduce a softening length into the force calculation. Once again, the merger problem is complicated by the two accelerated centres that are needed. Villumsen (1982) studied mergers between equal and unequal spherical systems using 2000 particles.

All the above methods simulate the evolution of purely stellar systems. A first attempt to include a dissipative interstellar medium in merger calculations has been made by Negroponte (1982) using a modified direct N-body code. He includes a population of "gas clouds" which have finite radii and can undergo dissipative collisions. His calculations show that a relatively small gas fraction can significantly enhance the interaction in galaxy collisions, and that much of the interstellar gas will fall to the centre of the remnant of a merger between spirals and will presumably form stars.

3 THE INTERACTION OF COLLIDING GALAXIES

When two galaxies collide, tidal forces couple their orbital energy to their internal degrees of freedom. The result of this coupling is most easily estimated in the impulsive approximation which assumes the orbital velocity to be rapid compared to internal velocities; the individual galaxies are heated at the expense of the orbit (Alladin 1965; see also the reviews cited above). In the strong collisions of greatest astronomical interest the impulsive condition is not satisfied however, and the dynamical situation is much more complex; the tidal field couples quasi-resonantly to the orbital motion of stars within each galaxy and can induce a strong collective response. One such response is the coherent bounce phenomenon seen in near head-on collisions between spherical systems (van Albada & van Gorkom 1977, White 1978, Miller & Smith 1980). When two galaxies overlap, the stars of each feel a strong inward force from the extra mass interior to their orbits; one dynamical time later when they bounce back the galaxies have separated and the extra mass has gone. The result is a forward spray of particles producing a characteristic "bowtie" morphology. Another example of this quasi-resonant coupling is the bridge and tail making process investigated by TT. In a slow encounter stars couple strongly to the tidal field if their galactocentric angular momentum is approximately aligned with the orbital angular momentum of the galaxy pair. Nearside stars tend to be captured onto the intruder while farside stars are thrown into extended orbits which lag behind the galaxy. The restricted 3-body experiments of TT showed that when a cold disk is subjected to such perturbation, its kinematic coherence can produce dramatic morphological structures. Except in a brief footnote these authors did not try to estimate the backreaction of the tail-making process on the binary orbit. Palmer & Papaloizou (1982) found from a linear calculation that in a direct parabolic encounter energy is transferred to the orbit from the disk. This result is not confirmed by fully self-consistent simulations of encounters between disk systems (Quinn 1982). White (1979) showed that strong spin-orbit coupling occurs in encounters between rotating spherical galaxies; corotating objects interact much more strongly than counterrotating ones. This dependence has also been found in all attempts to simulate the collision of disk or disk/halo systems (Gerhard 1981, Farouki & Shapiro 1982, Negroponte 1982, Quinn 1982). Farouki & Shapiro (1982) find an orientation dependence associated with the overlap of stellar distributions; the interaction between disk/halo systems correlates strongly with the degree to which the disks pass through each other.

A simulation of interacting spiral galaxies similar to that used by TT to model NGC 4676 (the "Mice") is shown in Fig. 1. Each diagram is a projection of a subset of the particles near the apocentre of the post-collision orbit. The top set shows particles from the spheroidal component of the initial galaxies while the lower set shows particles from their disks. The left four diagrams include particles from both galaxies, the centre four show particles from the corotating system and the right four show particles from the other system. In each set of six diagrams the top three show projections onto the orbital (x-y) plane and the lower three show projections onto the x-z plane. The responses of the two spheroids are quite similar; a few particles transfer allegiance and a broad tail forms behind each. The response of the disks is, however, extremely asymmetric. The corotating disk forms a massive tail and transfers many nearside particles to its opponent; the other disk makes a smaller tail and transfers only one particle. Tail formation and particle transfer are similar in self-consistent calculations and in the restricted 3-body experiments of TT (see Gerhard 1981, Negroponte 1982, and Quinn 1982); they account for most of the tidal coupling and strongly affect the later evolution of colliding systems.

4 MERGER REMNANTS

Interpenetrating collisions from near parabolic orbits lead to rapid coalescence; the central regions of the remnant then settle to a more or less steady state after a few dynamical times. Since the merging of two stellar systems is a dissipationless process in which little mass or energy is lost in escaping stars (e.g. White 1979, Negroponte 1982), several properties of merger remnants can be estimated very simply. The remnant mass, luminosity (before correction for aging of the stellar population) and binding energy are equal to those of the

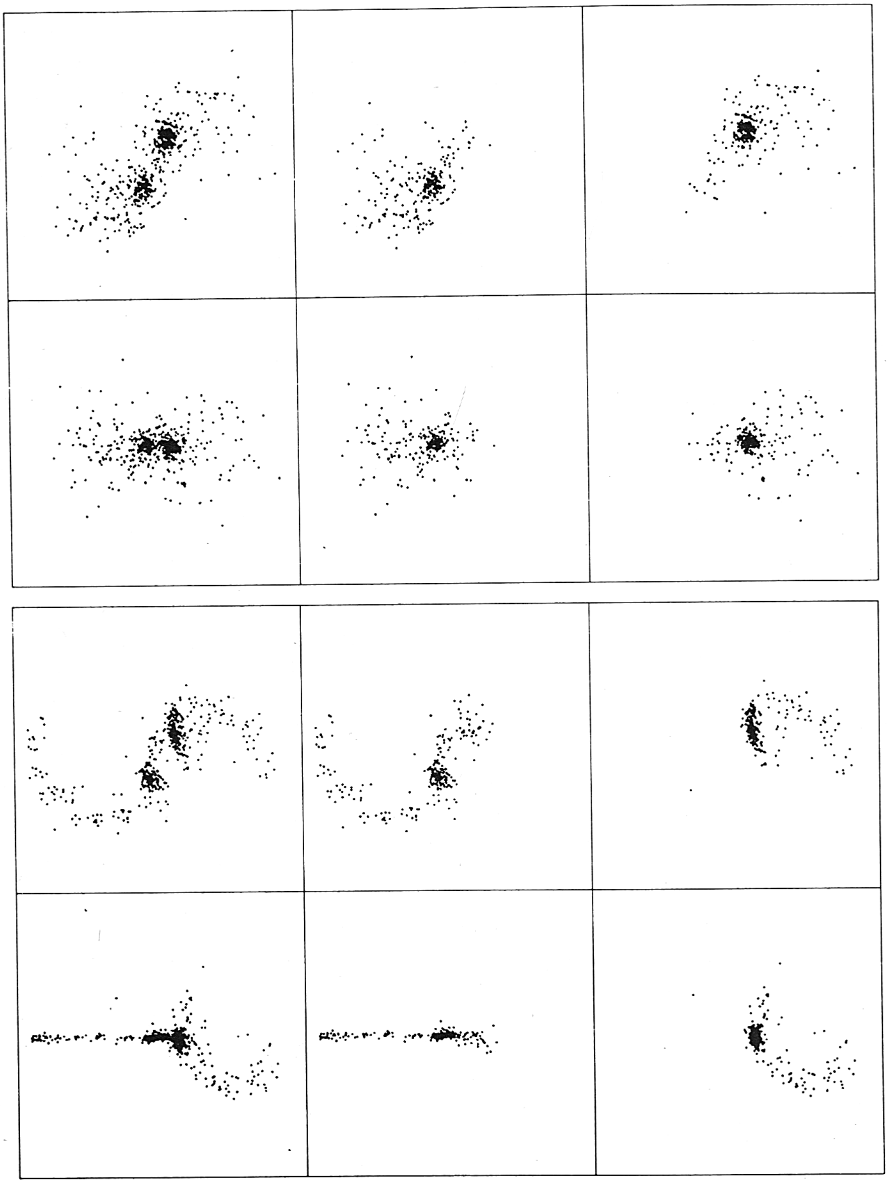

Fig. 1. Snapshots of a 1000-body simulation of a collision between two galaxies. Each system initially contained a near-exponential disk of 80 "gas clouds" and 170 "stars" and a non-rotating centrally concentrated spheroid made up of 250 "stars". Identical systems were placed on a parabolic orbit with pericentric distance 1.4 times their individual half-mass radius and oriented so that one disk corotated with the orbit and lay almost in its plane while the other was inclined at 80 degrees with its line of nodes along the pericentre vector. (Data from Negroponte 1982).

pair of progenitors. Thus if two similar systems merge from a parabolic orbit, the mass, the uncorrected luminosity and the gravitational radius of the remnant are twice those of each progenitor; the overall rms velocity dispersion is the same, and the mean surface brightness is half as big. Note, however, that the remnant will not usually be homologous to its progenitors so that these scalings need not apply to quantities such as the central surface brightness and central velocity dispersion. Large-scale simulations have demonstrated several general properties of merger remnants. Provided the relaxation process during merging is sufficiently violent, the density profile of the remnant follows a power law of index near -3 over up to two decades in radius (White 1978, 1979, Gerhard 1981, Villumsen 1982, Farouki & Shapiro 1982). In mergers of disk/halo systems both components end up with a density profile of this form. Its ubiquity may be due to its logarithmic divergence in mass on both large and small scales which allows non-homologous behaviour even when both mass and energy are conserved. Profiles of different form can occur in mergers of diffuse objects from bound initial orbits, in mergers of unequal systems, and in other less violent situations.

In general merger remnants tend to be ellipsoidal, although remnants of disk-disk mergers may have box-shaped isophotes (Quinn 1982). Near head-on collisions of spherical galaxies produce prolate (E3-4) remnants with weak streaming motions; more oblique collisions lead to oblate remnants with significant rotation (White 1978, 1979, Villumsen 1982). This result carries over to the more complex case of mergers between disk/halo systems according to Gerhard (1981), Farouki & Shapiro (1982) and Negroponte (1982), but Quinn's (1982) simulations of high angular momentum encounters produce rapidly rotating bar-like structures. The most likely source of this discrepancy would seem to be the very large potential softening used by Quinn, but the situation is still unclear. All workers agree that small pericentre encounters of disk/halo systems lead to triaxial bar-like remnants in which figure rotation and internal streaming depend on disk orientation and on the pericentre of the initial orbit. Negroponte also finds a dependence of remnant flattening on the inclination of the initial disks in the sense that high inclination disks produce rounder remnants.

Fig. 2 shows how the apparent shape and apparent rotation of merger remnants depend on viewing direction and on orbital angular momentum. These remnants all resulted from parabolic encounters of similar disk/halo systems. The upper panel plots points derived for 5 small pericentre mergers with roughly random initial disk orientations; the lower panel plots points for 5 large pericentre mergers. Each remnant was projected along 20 random directions and its apparent axial ratio, maximum rotation velocity and central velocity dispersion were measured. These data were then plotted up in the $V/\sigma - \varepsilon$ diagram so beloved of observers. Most of the remnants in the upper panel of Fig. 2 are prolate; they have large V/σ and large ε, large V/σ and small ε or small V/σ and large ε depending on the direction of viewing. Typical values of V/σ are quite small and are comparable with those seen in giant elliptical galaxies. The remnants in the lower panel are all oblate and

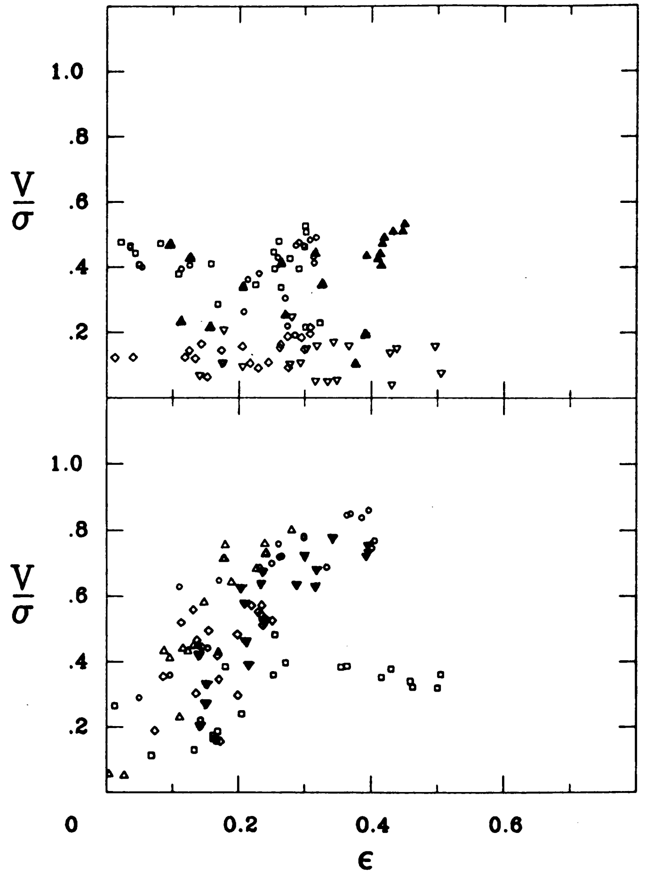

Fig. 2. V/σ – ε diagrams for the remnants of mergers between 250-body disk/halo systems. The initial galaxies had equal amounts of mass in a disk and in a non-rotating halo. All initial orbits were parabolic and all particles were counted when calculating the quantities shown. In each diagram all points plotted with the same symbol refer to the same remnant. (Data from Negroponte 1982.)

scatter along and somewhat below the "oblate line" discussed by Binney (1978); they have considerably higher values of V/σ. If any observed slowly rotating ellipticals formed by mergers of similar spirals, the angular momenta of the initial orbits must have been quite small. Aarseth and Fall (1980) argue that such an impact parameter distribution occurs naturally in a hierarchically clustering universe. Such slowly rotating merger remnants will be prolate objects.

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DISCUSSION

PALMER : What is the rotation curve in your disks, and how stable was it over the timescale of the interaction ?

WHITE : The rotation curve of the disk/halo galaxies used by John Negroponte for his thesis work rises rapidly over the inner 30 % by mass of the disk and thereafter remains essentially flat. When one of these "galaxies" is allowed to evolve in isolation, small clumps tend to appear and disappear in the disk despite the fact that its velocity dispersion corresponds to a value Q = 1.4 for Toomre's local stability parameter. These clumps drive a slow evolution of the disk towards a state of higher velocity dispersion and greater central concentration, but changes are not large over the timescale on which collision takes place in a merger simulation. Nevertheless, direct N-body codes are too crude to be able to simulate the evolution of a disk/halo galaxy properly ; we have to hope that the details of disk structure are of no great importance for the later evolution of a merging system.

SANDAGE : Is the effective surface brightness of the final daughter higher or lower than that of two identical spheroidal parents ? Observations show that $\langle SB \rangle_e$ of giant E galaxies (M_B brighter than −22) are lower by $\sim$ 1.2 mag than those of fainter E galaxies that are between M_B = −22 and −19.

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WHITE : As mentioned in my text, the mean surface brightness of the remnant (defined using the total luminosity and the half-light radius) is expected to be about a factor 2 smaller than that of the progenitors, in rough agreement with the numbers you quote. It is important to remember that this scaling may well not apply to the central surface brightness. Predicting the surface brightness of the remnant of a spiral-spiral merger is more tricky, but when allowance is made for the large change in morphology and the fading of the stellar population, the remnant surface brightness appears too low compared with that of normal ellipticals of the same luminosity ; a related and more serious problem is that the remnant velocity dispersion is predicted to be too low.