Tidal Interactions and the Merging of Galaxies

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Tidal interactions and the merging of galaxies

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Interpenetrating encounters between galaxies may occur frequently in groups and clusters of galaxies, and will be particularly common if most galaxies possess extended massive halos. When the encounter velocity of two galaxies is comparable with the velocity dispersion of the stars they contain, collisions are highly inelastic and may lead to a merger between the two objects. Such mergers can be investigated by direct numerical simulation. The coalescence of two similar 'galaxies' from a bound or parabolic initial orbit usually produces a centrally condensed oblate spheroidal system whose structure depends only weakly on that of the initial objects. Such mergers give rise to galaxies rotating as slowly as observed systems only if the initial impact parameter of the orbit is much smaller than is necessary to produce a strong interaction.

As has been emphasized in other papers in this volume, the mass distribution in galaxies may be considerably more extensive than the light distribution that we can observe. In addition, the strong spatial clustering of galaxies causes most objects to find themselves in regions where the density of neighbours exceeds the mean cosmological density of galaxies by a large factor. These two circumstances suggest that close encounters of one kind or another may be a common feature in the life of galaxies, a suggestion that is strongly reinforced by the kind of detailed simulation of galaxy clustering described by Fall and Aarseth (this symposium). Except in rare rich clusters, the relative velocities of neighbouring galaxies are similar to or smaller than the random velocities of the individual stars within a galaxy. Thus during a close encounter we may expect a strong gravitational coupling between the orbital motion of the colliding objects and their internal degrees of freedom. This coupling gives rise to a tidal drag that removes energy from the orbital motion and deposits it within the galaxies. Two initially unbound objects can therefore become bound to one another during an encounter, and the orbit of a bound pair will decay in an accelerating spiral until the two galaxies merge (Alladin 1965; Toomre & Toomre 1972; Toomre 1977).

Two kinds of question are of immediate interest concerning the processes described above. The first concerns capture and merging rates in a population of galaxies, and can be answered by calculating capture cross sections for unbound orbits and decay rates for bound orbits as a function of parameters describing the structure and initial orbit of the interacting galaxies. Such calculations have been carried out analytically in various approximations (Alladin 1965; Alladin *et al.* 1975; White 1979*a*), and can be combined with any specific model of galaxy clustering to predict the incidence of mergers and the evolution of the galaxy population as a whole. One may then hope that comparison with observation will place interesting constraints on some of the input parameters. For example, the assumption that galaxies have large massive halos may lead to so many mergers that the final distribution is incompatible with observation (cf. White & Sharp 1977; White & Rees 1978). In the next paper Aarseth describes the results of a series of calculations of this type. The other kind of question that immediately comes to mind is concerned with the details of the structure of the end-product of a merger. Does this object resemble any observed galaxies? How do its properties depend on those of the initial galaxy pair? Many questions of this kind can be answered by direct numerical simulation of mergers, and here I report the results of an extensive series of experiments that follow the merging of identical spherical systems from bound or parabolic orbits (White 1978; White 1979*b*; see also van Albada & van Gorkom 1977; Toomre 1977).

For my numerical experiments a galaxy is represented in the computer by a cluster of N 'particles' which are assumed to interact through the gravitational potential

$$\Phi_{ij} = 1/(|\boldsymbol{r}_i - \boldsymbol{r}_j|^2 + 1)^{\frac{1}{2}}. \tag{1}$$

Their orbits are calculated by integrating the Newtonian N-body equations of motion by using a program developed by S. J. Aarseth. Equation (1) is modified from the standard point mass form for numerical convenience and to suppress unrealistic effects caused by close encounters between 'particles'. The resulting 'galaxies' can, of course, only be compared with real objects on scales larger than unity. In my models N is usually 250 for each 'galaxy', although simulations with smaller numbers of particles have also been run for test purposes. After it has been set up according to some prescribed initial conditions, a 'galaxy' is allowed to evolve on its own for a while so that it can mix thoroughly and come to equilibrium. Two such relaxed systems are then used as initial conditions for a merger calculation. I have tried merging 'galaxies' of varying initial density and internal velocity structure from a variety of bound and marginally bound initial orbits. I have also looked at mergers between rapidly rotating (but spherical) systems. In all my simulations the two initial galaxies were taken to have similar structure.

It emerges from these calculations that the interaction between two 'galaxies' on a bound or parabolic orbit is strong if the systems overlap significantly at closest approach, and leads to rapid coalescence. For encounters with non-zero impact parameter, the coupling between orbital motion and internal particle motions is found to be strongest when the angular momentum of a particle within its 'galaxy' is aligned along the relative angular momentum of the two 'galaxies'; the coupling is weakest in the converse case when these two angular momenta are antiparallel. This suggests that tidal effects in encounters between rotating galaxies will be strongest when the galaxies corotate with the orbital motion and weakest when they rotate in the opposite sense. Simulations show that this is indeed the case, and that the effective tidal couple between rotating 'galaxies' can vary by more than a factor of two depending on the relative orientation of the characteristic angular momenta. In a population of rapidly rotating objects, mergers between galaxies in which orbital and internal angular momenta add will thus be favoured over mergers in which they cancel. During a merger between initially bound or marginally bound objects, potential fluctuations modify individual particle orbits considerably, but they are unable to produce a large number of unbound particles. The maximum mass lost in escaping particles in my calculations was 12 % of the total mass in a parabolic encounter between corotating 'galaxies'; a more typical mass loss fraction was 6 %. The corresponding figures for angular momentum loss are 37 % and 20 % and are higher because escaping particles carry off more than their fair share of angular momentum.

The density structure of the final 'galaxies' in these simulations depends remarkably little on the structure of the initial objects or on their orbit. In all cases the merger product has a more concentrated core and more extensive outer regions than its progenitors, and over most of the system the run of density with distance from the centre is well described by a power law with slope near -3. This behaviour is quite close to that of the observed light distribution in elliptical galaxies, but it differs considerably from the 'isothermal' power-law slope of -2 which is often assumed to describe the density run in massive halos. Most of the final 'galaxies' can be represented reasonably well as axisymmetric oblate systems, although a head-on collision produced a prolate 'galaxy', and a parabolic collision with fairly small impact parameter evolved into a system that was nearly oblate in the outer parts but strongly triaxial and bar-like in the centre. The ellipticity of a merger product often seems to vary systematically with radius, but no clear pattern emerges when different simulations are compared. Although in general the most rapidly rotating objects are the most flattened, a one–one relation between rotation and flattening does not appear to hold. All of the merger products in my simulations rotate more rapidly than most observed elliptical galaxies (Bertola & Cappaccioli 1975; Illingworth 1977; Schechter & Gunn 1979). This is because the angular momentum associated with the orbital motion of the initial 'galaxies' can suffice to make the final object rotate quite rapidly without reducing significantly the strength of the tidal interaction between its progenitors. Thus if most elliptical galaxies are formed by mergers between comparable objects, it appears that their progenitors must have been aimed at each other much more accurately than is necessary to account for their merging (White 1979*a*). Such a situation is only plausible if the initial galaxies were always bound to each other and so always 'knew' that they were going to merge. As Aarseth shows in the next paper, a predominance of head-on collisions can occur quite naturally in this case. The resulting picture for the formation of a merged object is, however, essentially equivalent to a description in terms of the inhomogeneous collapse of a well defined unit (see, for example, the system studied by White (1976)) and differs fundamentally from the sort of picture proposed by Silk (1978) in which initially independent objects aggregate in a random fashion.

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