PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

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*Phil. Trans. R. Soc. Lond. A* 1980 **296**, 351-353
doi: 10.1098/rsta.1980.0180

*Phil. Trans. R. Soc. Lond.* A **296**, **351–353** (1980) [ 351 ]
*Printed in Great Britain*

# Cosmological *N*-body simulations of galaxy mergers

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Numerical *N*-body simulations of galaxy mergers have been performed for models that include the cosmological expansion. Even conservative cross sections give rise to a substantial proportion of merged objects that are tentatively associated with elliptical galaxies. The merging process is not confined to the early expansion phase when the velocity dispersion is small but also occurs inside groups that form by the growth of initial density fluctuations. A wide range of masses is obtained from an initial pseudo-random distribution of unit masses; this could account for the massive cD galaxies. The mergers occur predominantly from bound pairs in highly eccentric orbits and the resulting angular momentum is consistent with the small rotational velocities observed for elliptical galaxies.

The problem of cluster formation in an expanding universe is currently receiving considerable attention (see Aarseth *et al.* 1979). In these *N*-body simulations the force on individual objects is obtained by a direct summation of the Newtonian attractions, slightly modified to represent extended mass distributions. However, this simple treatment ceases to be a good approximation during close encounters when tidal effects come into play. The interaction between two such objects produces an increase of internal kinetic energy at the expense of orbital kinetic energy. In particular, inelastic encounters may result in the capture into a bound configuration from a previously hyperbolic orbit, and this may in turn lead to a completely overlapping system. This effect has been studied both analytically (Alladin 1965) and numerically (White 1978), the general conclusion being that actual galaxy mergers are possible for a range of parameters which may include those realized in the Universe.

In the present work, undertaken in collaboration with S. M. Fall, we are interested in the merger process within a cosmological framework. This approach is therefore a natural extension of previous computer simulations of the expanding universe. For reasons of simplicity, we neglect other inelastic effects, including mass loss, although an attempt has been made to include these processes (Roos & Norman 1979).

The computer models are characterized by a set of parameters describing the initial conditions. An initial system of $N = 1000$ identical mass-points is distributed at random within a sphere of radius $R_s$. The corresponding velocities usually conform to pure Hubble expansion, i.e. $\boldsymbol{v} = H_s \boldsymbol{r}$. The initial Hubble constant $H_s$ is chosen to give a specified value of the standard cosmological density parameter $\Omega_f$ at the end-point denoted by $R = R_f$. To simulate the dynamics of galaxies we employ an interaction potential

$$\Phi_{kl} = Gm_k m_l/[(\boldsymbol{r}_k - \boldsymbol{r}_l)^2 + \epsilon_k^2 + \epsilon_l^2]^{\frac{1}{2}}, \tag{1}$$

where $\epsilon_k$ is a softening parameter associated with the mass-point $m_k$. In the Plummer model which gives rise to this potential, $\epsilon = r_h/1.3$, where $r_h$ is the half-mass radius. We adopt a

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final system radius $R_f = 40$ Mpc, corresponding to the observed luminosity density of 1000 bright galaxies and $H_f = 50$ km s$^{-1}$ Mpc$^{-1}$. The equations of motion are integrated in co-moving form as an $N$-body problem (Aarseth 1979), thus giving complete solutions as a function of the expansion factor $R$. The boundary itself is assigned an initial velocity $V_s = H_s R_s$ and the subsequent expansion rate is assumed to obey the Friedman equations. We consider both closed ($\Omega_f = 1$) and open ($\Omega_f = 0.1$) models and adopt final expansion factors $R_f/R_s \approx 10$ and 22, respectively, in approximate conformity with previous work.

The merger cross section is based on the $N$-body simulations of White (1978) together with the collisionless experiments of van Albada & van Gorkom (1977) which are in essential agreement. We adopt a condition of the form

$$(v_p/v_c)^2 + (r_p/r_c)^2 \leqslant 1, \qquad (2)$$

where $v_p$ is the relative velocity at the pericentre separation $r_p$. From head-on collisions, $v_c = 1.16 v_e$, where $v_e$ is the escape velocity at $r = r_p$ for the potential (1). The critical impact parameter is taken as twice the sum of the two half-mass radii, i.e. $r_c = 2.6\ (\epsilon_k + \epsilon_l)$. If condition (2) is satisfied at pericentre, the two interacting bodies are instantly replaced by the combined mass, with the new velocity obtained from momentum conservation. The corresponding softening parameter is calculated by assuming energy conservation together with homology. In view of the uncertain status of the heavy halo hypothesis, we consider two alternative values for the initial softening parameter, i.e. $\epsilon/R_s = 1.3 \times 10^{-3}$ and $5.2 \times 10^{-3}$. With the adopted length scale this corresponds to half-mass radii of about 5 and 20 kpc for $R_f/R_s = 10$ (closed models) and a factor of two smaller for $R_f/R_s = 22$ (open models).

The initial fraction of bound pairs in a Poisson distribution is not significantly different in the open and closed models considered here. For a perfect Hubble expansion, these binaries start out in radial orbits, and provided the perturbation to the eccentricity by other neighbours is small, the return orbits may satisfy the merger condition even for quite modest half-mass radii. It is therefore not surprising that the early merger rate is still significant for the open models with small half-mass radii. Although this contribution is reduced as the initial bound pairs are depleted, the merger rate remains appreciable throughout. An increasing proportion of these events now occurs inside the groups that form by the growth of initial density fluctuations. Nevertheless only a small percentage of all mergers arise from hyperbolic encounters; this may be taken as an indication that the velocity dispersion in such groups is relatively low. In the models with pure Hubble expansion the proportion of merged bodies reaches 10–15 % at $R/R_s \approx 2$. This increases to 22–38 % at $R/R_s \approx 10$, with the smallest value for the open model with small half-mass radii. The proportion of merged bodies does not grow appreciably during the subsequent expansion; i.e. the gain from previously unmerged bodies is to some extent cancelled by mergers of higher multiplicity.

The models discussed above have initial velocities satisfying the perfect Hubble law, whereas perturbations during the earlier phase would generate peculiar motions and thereby reduce the merger rate. Several models with 2.7 % of the initial kinetic energy in random motions have been studied, corresponding to peculiar velocities *ca.* 500 or *ca.* 1000 km s$^{-1}$ for open or closed models respectively. The fraction of mergers for a closed model with large half-mass radii is then reduced from 38 % to 17 %, whereas the respective final ratios are 24 % and 8 % for an open model with small half-mass radii. Although these reductions are considerable, it may be argued that such initial peculiar velocities are excessive. Thus if we adopt Toomre's

(1977) suggestion that elliptical galaxies are formed by the merging of spirals, it appears that the present models can account for the relative distribution of these objects.

Because of run-away effects, the maximum mass may become quite large, i.e. about 80 initial mass units for $\Omega_f = 1$, $r_h = 20$ kpc compared with 12 mass units for the open model with small half-mass radii. It is therefore tempting to extend Toomre's idea and associate the extreme cases of multiple mergers with massive cD galaxies that dominate many clusters. From the present models the mass–radius relation is well approximated by $m \propto r_h^{1.2}$, in qualitative agreement with the observed trends (see Aarseth & Fall (1980) for a more detailed discussion).

The present simulations also provide information about the angular momentum ($\boldsymbol{J}$) of merged objects, which is obtained by combining the intrinsic spins with the orbital component. The final distribution, measured by the usual dimensionless parameter $\lambda^2 = |E|\, J^2/G^2m^5$ (where $E$ is the internal energy), is independent of mass. Moreover, the results indicate that rotation would not be significant, i.e. $\langle\lambda\rangle \approx 0.07$. This is in qualitative agreement with recent observations of rotation curves for elliptical galaxies. The main reason for the low $\lambda$ values can be traced to the highly eccentric orbits of the merging bodies. Encounters of this type therefore have smaller impact parameters than are necessary for strong interactions, as demanded to produce elliptical galaxies with low rotational velocities (White 1979).

In conclusion, I emphasize that the present merger models are based on simple assumptions. Additional effects must be included to make the simulations more realistic. However, the results discussed here already indicate that the merger process may be highly efficient for a range of conditions. This places severe limitations on the possible extent of galactic halos, which can only be avoided by employing drastically different assumptions.

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