THE DYNAMICAL EVOLUTION OF CLUSTERS OF GALAXIES

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1. INTRODUCTION.

Typical orbital periods for galaxies in rich clusters are observed to be several billion years. Consequently these large systems have had little time to come to equilibrium, and indeed if they formed from small initial density perturbations they must have taken a substantial fraction of the age of the Universe to separate from the Hubble flow and recollapse (Gunn and Gott 1972). Despite the relatively short time available, dynamical effects can cause appreciable evolution both in the distribution of galaxies within clusters and in the observable features of individual galaxies. The overall aspect of a cluster changes as violent relaxation irons out inhomogeneities and establishes a relaxed core-halo structure. At the same time collisional relaxation causes massive galaxies to lose energy to lighter objects in an attempt to reach equipartition of kinetic energy, and to spiral towards the cluster centre. These processes are relatively easy to analyse in any particular scheme for cluster formation, and below we concentrate on comparing their predicted effects with observation.

Dynamical effects on individual galaxies are more complex and, in addition, depend on the cluster formation and relaxation processes. Gas may be stripped from spirals both by direct galaxy-galaxy collisions (Spitzer and Baade 1951) and by the ram pressure of an intracluster gas (Gunn and Gott 1972). Collisions will also result in the removal of the outermost parts of all galaxies by tidal effects and the pumping of energy into their central regions (Gallagher and Ostriker 1972, Richstone 1976, Biermann and Silk 1976). Individual cluster galaxies may merge with their satellites or binary companions, or be assimilated by a central cD galaxy (Ostriker and Tremaine 1975, White 1976a). The timescales for all these processes are such that they may be important in at least the central regions of most clusters. The details of their observational implications still, however, remain to be worked out.

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2. N-BODY MODELS FOR CLUSTERS.

The simplest model to use to study clusters of galaxies is one in which the galaxies are assumed to contain all the mass and are treated as fuzzy particles interacting only through a softened gravitational potential. The evolution of any initial configuration can be studied in this case by direct integration of the equations of motion on a computer. Such calculations (reviewed by Aarseth and Lecar 1975) show that this simple model can give an adequate fit to the overall structure of rich relaxed clusters. A recent 700 body simulation by White (1976b) included enough particles to model a rich galaxy cluster, used a mass spectrum based on the luminosity function of observed clusters, and was started with initial conditions intended to mimic an initially expanding protocluster at the onset of galaxy formation. This calculation showed that if galaxy formation in a typical protocluster began significantly before maximum expansion, the cluster would collapse in a very inhomogeneous way through the condensation and progressive amalgamation of subclusters. After recollapse most of the substructure of the model was destroyed, but some overall anisotropy persisted. This suggests that the apparently elliptical structure seen in some dense clusters (Bahcall 1973, Austin and Peach 1974, Gregory and Tifft 1976) may be a result of the details of their formation rather than of rotation.

The kind of fit to observation that can be obtained with such a model may be seen in Fig. 1 which compares the predicted radial distributions of line of sight velocity dispersion and of number and mass density with data on the Coma cluster. Also shown are the projected isothermal sphere found by Bahcall to fit the number counts of galaxies near the cluster centre and the N-body model of Peebles (1970) which contained 300 equal mass particles. Although the general agreement is quite satisfactory there are two important differences between the model and the observed cluster. The secondary maximum of the observed density profile at about one degree from the cluster centre cannot be matched without the inclusion of some new physical effect. (Possibilities might be the stripping and consequent dimming of spirals as they move through an intracluster gas, or some kind of continual infall into the outer parts of the cluster). The N-body results also contradict observation by displaying extensive mass-segregation. This can be seen in Fig. 1 as a variation of mean mass with radius, and detailed analysis shows it to be quite inconsistent with the weak luminosity segregation that is observed (Bahcall 1973, White 1976c). Since mass segregation arises through collisional relaxation, the explanation of this discrepancy must be sought in the relaxation rate of the system.

3. RELAXATION AND DYNAMICAL FRICTION.

In a self gravitating cluster of objects with a wide mass range the main secular effect of collisional relaxation is to make the heaviest particles lose energy to lighter cluster members. This can

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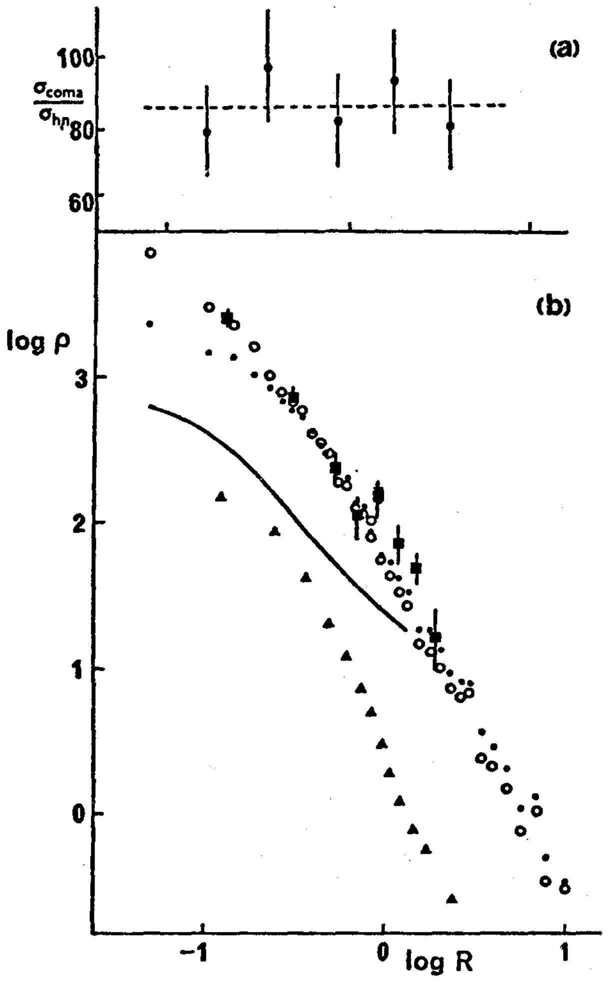

Fig. 1 (a). The ratio of the line of sight velocity dispersion in the Coma cluster to that in the 700 body model of White (1976b) as a function of radius. The unit of radius is 49 arc minutes and the model dispersion decreases by a factor of two between the innermost and outermost points. The error bars give the one sigma sampling errors in the data (taken from Rood et al 1972).
(b) The projected mass (open circles) and number (filled circles) density profiles of the same model are fitted to Oemler's (1974) luminosity profile for Coma (filled squares). Also shown with arbitrary density normalisation are a projected isothermal sphere of core radius 6 arc minutes (smooth curve) and Peebles' (1970) "standard" model scaled to have the same virial radius as the observations (filled triangles).

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be considered as resulting from an effective frictional force which for a massive object moving through an infinite gas of lighter objects is given by

$$m\, d\underline{v}/dt = -\, 4\pi G^2 m^2 \frac{\underline{v}}{|\underline{v}|^3} \ln \Omega\, \rho(|\underline{v}|) \qquad (1)$$

where m and $\underline{v}$ are the mass and velocity of the heavy object, Ω is the ratio of the maximum and minimum impact parameters for which encounters are effective, and $\rho\ (|\ \underline{v}\ |)$ is the mass density of objects with speeds less than $|\ \underline{v}\ |$ (Chandrasekhar 1942). The evolution rate implied by (1) can be illustrated by the simple model of a uniform spherical cluster of mass M and radius R. If we define a frictional relaxation time by $T_f = E/(dE/dt)$ where E is the total energy of typical particle, then taking $E \simeq -\, GMm/R \simeq -mv^2$, $\rho \simeq 3M/8\pi R^3$, and the orbital time $T_o \simeq 2\,\pi\, R/v$ we obtain

$$T_o/T_f \;\simeq\; 3\,\pi \ln \Omega\ (m/M) \qquad (2)$$

Since an appropriate value of ln Ω might be about five, a particle containing one per cent of the cluster mass will spiral into the centre in a very few orbits if most of the cluster mass is contained in lighter objects.

The brightest galaxy in the Coma cluster contributes almost 3 per cent of the cluster light so that strong segregation will clearly occur in any dynamical model of the cluster in which the galaxies are assumed to contain all the mass in proportion to their luminosities. If we wish to believe that there is a strong correlation between galactic mass and galactic luminosity, we must decrease T_o/T_f by a substantial factor in order to get a model which is compatible with the lack of segregation in observed clusters. This clearly implies that the mean mass-to-light ratio of the brighter galaxies in a cluster must be much less than that of the cluster itself. As was concluded by Rood et al (1972), most of the mass binding clusters cannot be attached to the individual galaxies.

4. A MODEL FOR THE MISSING MASS.

If the unseen intergalactic medium which binds rich clusters is made up of objects less massive than galaxies, then equation (1) can be used to describe the interaction of the galaxies with the background. The lack of observed segregation implies that the distribution of the fainter galaxies can have been little affected by the unseen material and so will give a good indication of the initial galaxy distribution. White (1976a) has calculated models for the evolution of the galaxy distribution in a spherical cluster based on an isothermal distribution of the unseen material. The sensitivity of the amount of mass segregation in these models to the mean mass-to-light ratio assumed for the galaxies is illustrated in Fig. 2 (taken from White 1976c). This shows the predicted ratio of the amount of light within 15 arc minutes of the cluster centre to that between 15 and 35 arc minutes

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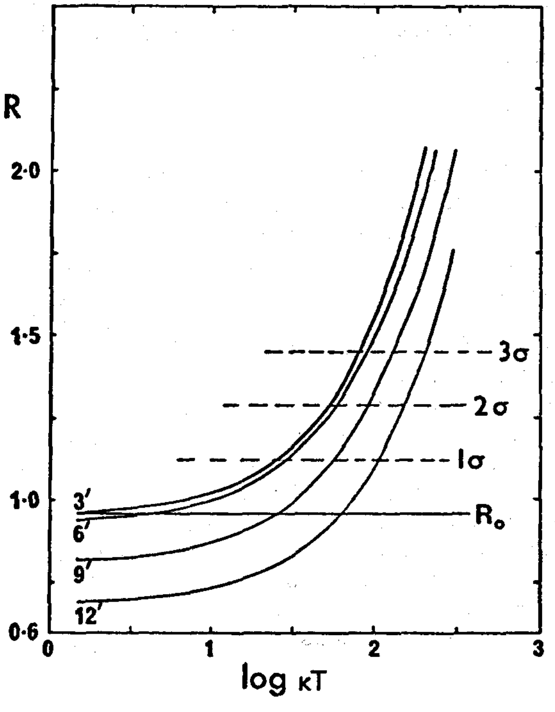

Fig.2. The values predicted by the models of White (1976a) for the ratio, R, of the total galactic light within 15 arc minutes of the centre of the Coma cluster to that between 15 and 35 arc minutes. The abscissa is the decimal logarith of the product of the mean visual mass-to-light ratio of the galaxies in solar units and the effective time of evolution in units of 10^{10} y. $R_{\odot}$ is the observed field-corrected estimate of R, and the 1, 2 and 3 sigma upper limits on its value include uncertainties due to Poisson statistics and to a 50 per cent uncertainty in the field correction. The four curves are for the four given values of the core radius.

as a function of the product of the galactic mass-to-light ratio and the time of evolution. The four curves are for four different core radii of the initial distribution assumed for the galaxies and for the missing mass. The observed ratio is also shown for the Coma cluster where galaxy counts give a present core radius of 6 ± 0.6 arc minutes (Bahcall 1973). Since the time of evolution must be of the order of the Hubble time, values greater than 30 for the mean mass-to-light ratio of the galaxies are ruled out unless the spatial distribution of the missing mass is and always was very different from that of the galaxies. (Here and below we take H_o = 50 km/sec /Mpc, $q_o << \frac{1}{2}$). The cluster mass-to-light ratio is 258 ± 36 (White 1976b) so that 20 per cent would seem to be a conservative upper limit for the amount of cluster mass which can be attached to galaxies at the present time.

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Notice that this does not exclude the possibility that all the cluster material was originally attached to galaxies, but that most of it was tidally stripped from their outer parts at an early stage of cluster evolution (c.f. Richstone 1976, Biermann 1976).

5. THE INTERGALACTIC BACKGROUND.

Since most of the cluster mass appears to lie in a diffuse background between the galaxies, it is interesting to see what limits can be placed on its form. Radio and X-ray data exclude the possibility that it all be gaseous unless most of it is in dense optically thick clouds (Tartar and Silk 1974). If it is composed of objects of normal stellar density, then they must be at least a few centimetres in radius to avoid excessive obscuration of background galaxies (Peebles 1971). Recent measurements of the diffuse light in clusters agree that it can contribute only a small fraction of the total cluster luminosity. Oemler (1973) detected a diffuse background which might contain up to 35 per cent of the light of the cluster A2670, whilst photoelectric mapping of part of the Coma cluster by Melnick, White and Hoessel (to be published) gave an upper limit of 20 per cent for the amount of cluster light which might come from a true intergalactic background. Since this background contributes at least 80 per cent of the mass it must have a visual mass-to-light ratio of more than 1,000. If it is made up of stars they must be less massive than 0.1 $M_\odot$.

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