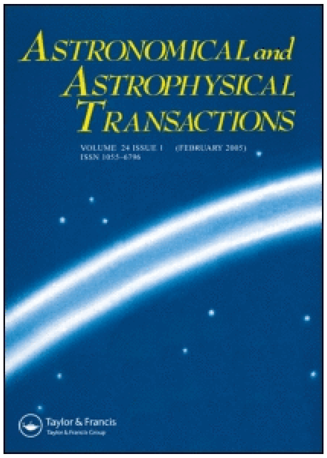

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DARK MATTER IN CLUSTERS OF GALAXIES

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Dark matter has been detected in galaxies and clusters of galaxies, where it dominates gravity on scales larger than several kpc. Most of the dark matter in clusters has been stripped from the halos of massive galaxies. The time-varying dark matter potential affects the appearance of luminous galaxies. Thin disks of spirals thicken and gain velocity dispersion. In small galaxies tidal heating may lead to complete dissolution. Thus, dark matter plays a critical role in galaxy formation and evolution.

KEY WORDS Dark matter, cluster of galaxies

1 THE CASE FOR DARK MATTER

Most of what we know about the Universe comes from the light it emits. Yet, most of its mass is invisible. The Universe is dominated by dark matter. How do we detect this unseen mass and what form does it take?

If the only certain property of dark matter (DM) is its mass, we can define DM as any form of matter whose presence is inferred solely from its gravitational effects (Binney and Tremaine 1987). Several lines of evidence make the case for DM:

(1) In 1933, Fritz Zwicky found that the velocity dispersion of galaxies in the Coma cluster is higher than would be expected from the Virial theorem, if all the mass was contributed by the luminous galaxies.

$$\frac{GM_{\rm cl}(r)}{r} \sim \sigma_{\rm gal}^2.$$

He suggested that there was an extra concentration of mass in the cluster, with the resulting mass-to-light ratio being extremely high:

$$\left(\frac{M}{L}\right)_{\rm cl} \sim 300\frac{M_\odot}{L_\odot}.$$

This finding has been subsequently confirmed for other clusters.

(2) The X-ray emitting gas in clusters of galaxies indicates a similar amount of mass. The gas is assumed to be in hydrostatic equilibrium with the cluster potential, usually a good approximation, and its temperature relates to the total mass through the Virial theorem.

$$\frac{GM_{\mathrm{cl}}(r)}{r} \sim kT.$$

The amount of the X-ray gas is large, about 10 times the mass of the luminous galaxies.

(3) A direct measure of the cluster mass comes from gravitational lensing. The technique of the gravitational lens reconstruction provides the value of the gravitational potential on the line of sight of the lensed object, usually a quasar or a background galaxy. Remarkably, this method yields roughly the same mass in the clusters where all three methods have been tried. Lensing results show that only a tiny fraction of the cluster mass is associated with luminous galaxies, about 2%.

(4) On the galactic scales a direct measure of the mass is provided by the rotation curve. In almost all spiral galaxies studied, the velocity of rotation of the stars and gas at large radii does not decline in agreement with Kepler's law. The 21 cm line emission of neutral hydrogen extends beyond the limit of light distribution and shows no sign of declining rotation curve. Instead, it is essentially flat, $V_{\mathrm{rot}} = \mathrm{const}$, implying that mass still grows linearly with radius. Thus, for spiral galaxies the mass-to-light ratio is also very high:

$$\left(\frac{M}{L}\right)_{\mathrm{sp}} \sim (10\text{–}30)\frac{M_\odot}{L_\odot}.$$

In elliptical galaxies, the velocity dispersion of stars points to even higher values:

$$\left(\frac{M}{L}\right)_{\mathrm{ell}} \sim (20\text{–}100)\frac{M_\odot}{L_\odot}.$$

Can all this mass be accounted for by the known astronomical objects? The main-sequence stars in the solar neighborhood have an average mass-to-light ratio $\sim M_\odot/L_\odot$. Including the degenerate stars (white dwarfs, neutron stars, and black holes) we can push this value up, but no higher than $\sim 10M_\odot/L_\odot$. Brown dwarfs, objects with masses $< 0.08M_\odot$ unable to ignite hydrogen in their cores, are unlikely to contribute much mass. Recent stellar surveys show very few stars less massive than $0.2M_\odot$. Also, planets and 'jupiters' are too small to affect the global mass-to-light ratio. Finally, the interstellar medium (gas and dust) in many galaxies may contribute as much mass as the stars. Thus, the luminous objects can be marginally consistent with the lower estimate of M/L in spiral galaxies, but the majority of galaxies have even larger masses.

Summed over all galaxies, the contribution of the luminous matter to the mean density of the Universe in units of the critical density ($\Omega \equiv \rho_{\mathrm{m}}/\rho_{\mathrm{cr}}$) is small,

$$\Omega_{\mathrm{lum}} \approx 0.005\text{–}0.1.$$

The theory of primordial nucleosynthesis (see Peebles 1993), very successful in predicting element abundancies, implies the total baryon mass density

$$\Omega_b \approx 0.02h^{-1} \approx 0.05$$

for the Hubble constant $h \equiv H_0/(100 \text{ km s}^{-1} \text{ Mpc}^{-1} = 0.6$. Thus, at least 80% of baryonic matter is dark.

Recently, distant supernovae type Ia, with redshifts up to $z = 1$, have been used to infer the total mass density of the Universe. The preliminary results of two independent groups indicate $\Omega_0 \approx 0.3$ (Garnavich *et al.*, 1998; Perlmutter *et al.*, 1999). They favor a flat geometry with a positive cosmological constant, $\Omega_0 + \Omega_\Lambda = 1$. This result is also supported by the large scale cosmic flows, and by the abundance and evolution of galaxy clusters. In turn, this means that $\approx 97\%$ of all matter in the Universe is dark.

There are many candidates for the dark matter particles (Hawley and Holcomb 1998). They could be baryonic, such as the massive compact halo objects (MACHOs), and non-baryonic, called weakly interacting massive particles (WIMPs), such as the massive neutrinos, Higgs bosons, axions, and others. I will not discuss here which particles are the more likely DM candidates; this in itself is a very active area of research. But irrespective of its exact nature, dark matter reveals itself via its gravitational interaction.

2 HIERARCHICAL FORMATION OF GALAXIES AND CLUSTERS

Observations of the cosmic microwave background radiation show that the Universe was very smooth at the epoch of last scattering, with a level of density fluctuations $\sim 10^{-5}$. The self-gravitating structures we see in the Universe now, such as galaxies and clusters of galaxies, must have formed from those initial perturbations. Causal communication during gravitational collapse requires that modes of growing perturbations have scales smaller than the Hubble length, a current size of the Universe ($l_H = ct_H$). As the Hubble length increases with time, larger and larger structures can start forming.

If the DM particles move with high velocity, they can diffuse from regions of high density to regions of low density, thus smoothing inhomogeneities. This effect leaves only large enough structures to be able to survive and grow. The popular model of dark matter assumes that it is kinematically cold, i.e. that the DM particles have low velocities when they decouple from the background photons. Because of these small velocities, the particles can form small structures early on. These small self-gravitating blobs collapse and later merge into galaxies and then clusters of galaxies.

Baryonic gas falls into the gravitational potential of dark matter halos, where it cools and collapses even further. Ultimately, the gas becomes self-gravitating and forms stars. The galaxies are born. Still, on scales larger than several kpc most of the mass is dark. Therefore, the formation and evolution of galaxies is closely linked to the dynamics of dark matter.

Similarly, clusters of galaxies form by accumulation of mass from the infalling galaxies and filaments connecting them. They go through several stages of hierarchical formation:

$z \sim 5$–10: galaxies start to assemble, clusters do not yet exist
$z \sim 1$–3: galaxies fall into the clusters
$z < 1$: continuous infall of galaxies.

3 EVOLUTION OF DARK MATTER IN CLUSTERS

The most direct way to study non-linear evolution of dark matter is via numerical simulations. As an example, I present here three model clusters of galaxies. They are all constructed to be of similar size and mass to the nearby cluster in the constellation Virgo. The Virgo cluster is one of the most typical clusters in the Universe, with a line-of-sight velocity dispersion of galaxies of 700 km s^{-1}. The initial density fluctuations are constrained to produce a 3σ peak in the center with a power spectrum corresponding to the three cold dark matter cosmologies: a critical density model $\Omega_0 = 1$, an open model $\Omega_0 = 0.4$, and a flat model $\Omega_0 = 0.4$ with a cosmological constant.

Figure 1 shows the cluster density plots at the end of the simulations. The low density models allow more time for the clusters to assemble and virialize. In contrast, in the $\Omega_0 = 1$ model the cluster is still irregular, with a large group of galaxies on the right falling into it. This is a generic feature of the hierarchical formation scenario which predicts a continuous infall of galaxies into the cluster.

In this example, the clusters are simulated using a fast, but low-resolution, Particle-Mesh code. This leads to some substructure in the center being erased by the numerical 'overmerging' effect. Most advanced recent simulations have overcome this problem and show a large variety of self-gravitating halos and clumps inside the clusters. As a result, galaxies have lots of close encounters with massive halos. However, very few galaxies merge with each other, the merger probability is only $\sim 10^{-3}$ per encounter. This is mainly due to large speeds at which galaxies collide. Their stellar components pass through each other without being able to form a bound system. Thus, mergers do not seem to dominate the dynamical evolution of galaxies. Instead, the main effect is due to tidal interactions.

Even when a galaxy passes at a safe distance from the perturber, the stars in it experience a tidal force

$$\boldsymbol{F} = -\frac{\mathrm{d}^2\Phi_{\mathrm{ext}}}{\mathrm{d}\boldsymbol{R}\,\mathrm{d}\boldsymbol{R}} \cdot \boldsymbol{r},$$

where Φ_{ext} is the external potential creating tides, $\boldsymbol{R}$ is the position of the center of mass of the galaxy, and $\boldsymbol{r}$ is the position of a star within the galaxy. Integrated over the duration of the encounter, this tidal force causes the increase of the unordered kinetic energy of stars and the reduction of the binding energy of the galaxy as a

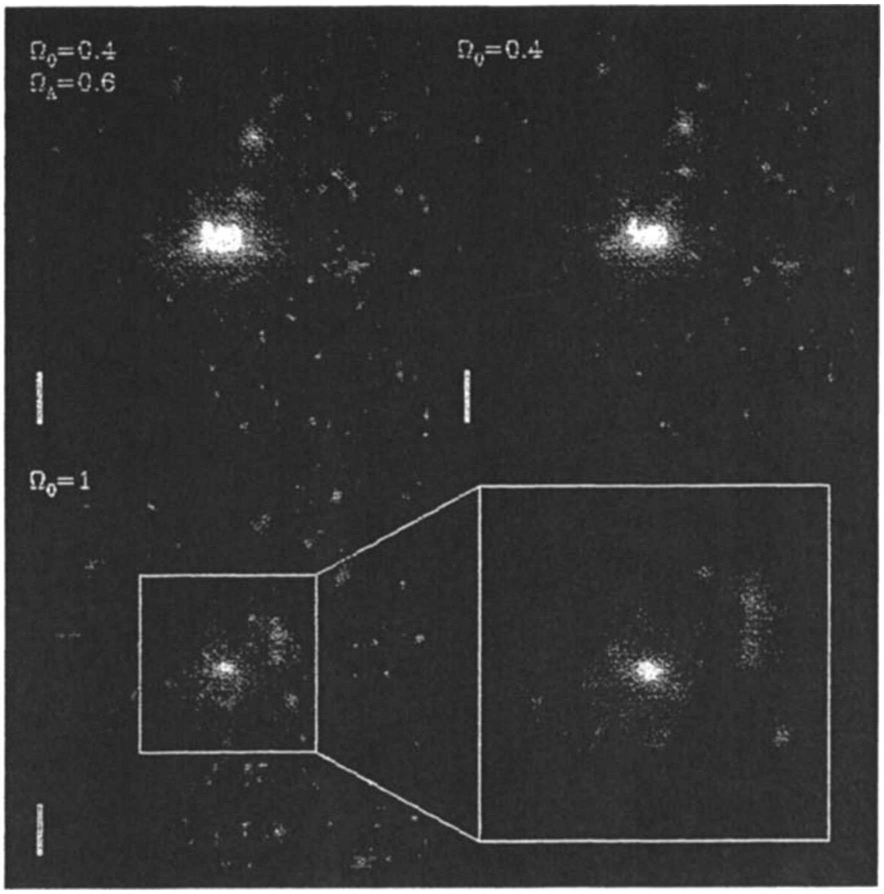

Figure 1 The surface density maps of the three simulated clusters at $z = 0$. Saturated white regions are at least 200 times denser than the average; regions below the mean density are black. The size of the windows is $8h^{-1}$ Mpc. The lower right panel shows the enlarged view of the inner region of the $\Omega_0 = 1$ cluster. Thick bars in the lower left corners of each panel indicate $1h^{-1}$ Mpc.

whole. This effect leads to the secular kinematic heating of the stars as well as the dark matter particles.

The same effect applies to the encounters with the large clumps of dark matter, such as the halos of the infalling groups of galaxies. Also, a comparable contribution to the tidal force comes from the global cluster potential. The time variation of the dark matter potential during the hierarchical formation leads to strong tides affecting essentially all galaxies and all halos in the cluster.

Figure 2 illustrates the dynamics of cluster formation in the flat cosmological model. At redshift $z = 5$ the density perturbations are weak and individual halos are well separated. By redshift $z \sim 2$, the cluster is already significantly denser than the surrounding media. In the last panel the cluster is several hundred times

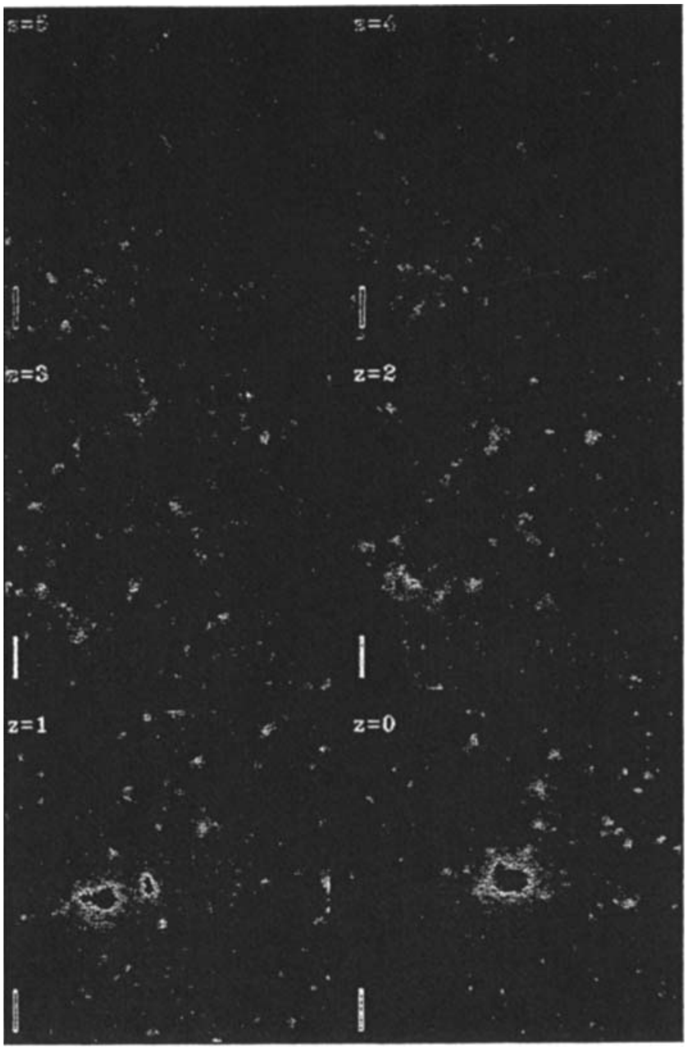

Figure 2 The projected density maps of the $\Omega_0 = 0.4$, $\Omega_\Lambda = 0.6$ cluster at six successive redshift slices. The window size and the brightness stretch are as in Figure 1.

denser than the average. As the galaxies fall into the cluster, they experience a strong variation of the global tidal force. For each galaxy the force is different, depending on the details of the trajectory. Since the mean density falls as the Universe expands, the earlier the galaxy enters the cluster, the stronger is the tidal force.

For each galaxy in these simulations, I can extract the tidal field along its trajectory in the cluster. Since the galactic halo contributes to the total potential, the value of $\Phi_{\rm ext}$ should be corrected for the effects of self-interaction. The resulting tidal force for one large galaxy and one small galaxy in the flat model is shown in

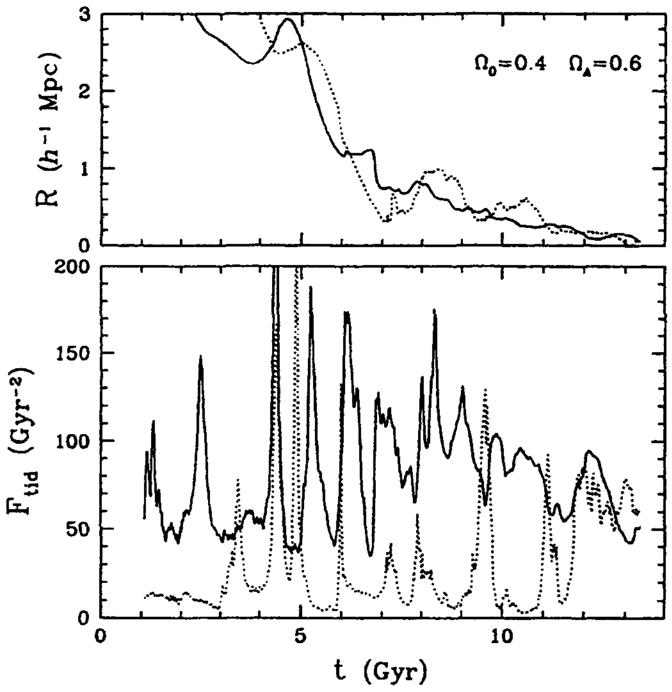

Figure 3 Tidal field around the large (solid line) and dwarf (dots) galaxies in the $\Omega_0 = 0.4$, $\Omega_\Lambda = 0.6$ cluster. Upper panel shows the distance from the final center of the cluster.

Figure 3. Here $F_{\rm tid}$ refers to the trace of the tidal tensor, $d^2\Phi_{\rm ext}/dR_i\,dR_i$.

The tidal force varies with time and shows many narrow peaks. The peaks are stronger and narrower at early times, when the galactic halos are not yet stripped and the average density is high. In the $\Omega_0 = 1$ simulation, the peaks are less pronounced because in this model the cluster forms later and the average density is lower. The difference in the cluster formation epoch also allows galaxies in the low density models to spend more time inside the cluster until the present and experience more tidal interactions.

The maxima of the tidal force do not always correlate with the closest approach to the cluster center (upper panel). They are produced to a large extent by the local density structures, such as the massive galaxies and the unvirialized remnants of groups of galaxies.

Close encounters between the galaxies are significantly intensified by the substructure, with about 10 encounters per galaxy per Hubble time with the impact parameter less than 10 kpc. These very close encounters contribute an important amount, from 10 to 50%, of the tidal heating of galaxies.

As with the strength of the tidal maxima, tidal heating is stronger overall in the low Ω_0 clusters.

Table.

Ellipticals	*Spirals*
'pressure' supported	rotationally supported
kinematically hot ellipsoids	kinematically cold disks
found preferentially in clusters	found preferentially in the field
(high-density environment)	(low-density environment)

4 TIDAL EFFECTS AND MORPHOLOGY OF GALAXIES

In 1936, Edwin Hubble introduced a morphological classification scheme, in which he divided all regular galaxies into the spiral and elliptical types. Spiral arms in one type, emphasized by the bright young stars, contrast with the smooth distribution of mostly old stars in the other. In addition to the different appearance, the two types have different dynamical properties. While in spiral galaxies, stars settle into a rotating disk, in ellipticals they support themselves against gravity using 'pressure', or random velocity dispersion, similar to molecules in the air. In effect, the difference is between the ordered and chaotic motion. Between the ellipticals and spirals lie lenticular S0 galaxies, with thick disks but no spiral arms and no star forming regions.

Included in Hubble's classification was the idea that one type of galaxy transforms into another and that different types merely represent different epochs in the galactic life. Another piece of evidence that evolutionary effects may be at work is the morphology-density relation. In the local Universe, elliptical and lenticular galaxies are found preferentially in clusters, while spirals are dominant in the field. Observations of high-redshift clusters by the Hubble Space Telescope reveal an overabundance of spirals by a factor of 2–3, and the corresponding underabundance of S0 galaxies, relative to the nearby clusters.

If all galaxies form initially as spirals, tidal heating in the high-density environment can potentially add enough random energy to puff up thin disks into an ellipsoidal shape. Thus, tidal interactions may be responsible, at least partly, for the observed morphological transformation of galaxies in clusters. But does this follow from the hierarchical scenario described above? Do spirals really transform into the ellipticals? I will address these questions with another set of N-body simulations.

Using a high-resolution galactic N-body code, I resimulate several individual galaxies with 2×10^6 particles. In addition to the internal dynamics of the galaxies, I impose the external tidal field derived along their trajectories in the cluster simulations.

These disk galaxies start off with the extended dark matter halos. In agreement with analytic expectations, tidal heating unbinds and removes a large part of the halos. While the inner regions are almost unaffected, the outer halos are truncated at a critical radius

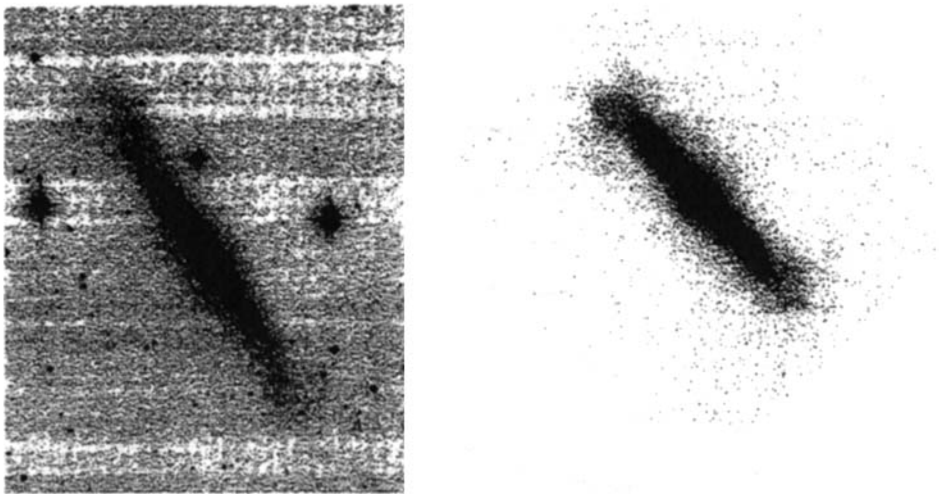

Figure 4 *Left*: S0 galaxy NGC 4762. *Right*: Galaxy in the $\Omega_0 = 1$ simulation.

$$R_t \sim 100 \frac{\sigma_{\rm gal}}{\sigma_{\rm cl}} \text{ kpc} \sim 20 \text{ kpc}$$

depending on the cluster and galactic velocity dispersions, $\sigma_{\rm cl}$ and $\sigma_{\rm gal}$, respectively. Within the truncation radius, the halo velocity dispersion stays roughly the same. The halo mass remaining bound,

$$M_t \approx \frac{\sigma_{\rm gal}^2}{G} R_t \sim 2 \times 10^{11} M_\odot,$$

can be much smaller than initially. Since the halo stripping is universal for all cluster galaxies, tides remove a large fraction of the galactic mass. Therefore, most of dark matter in clusters at present is not bound to the galaxies.

Figure 4 shows the stellar disk of a Milky Way-type galaxy in the $\Omega_0 = 1$ simulation. It looks very similar to an S0 galaxy NGC 4762 from the Bubble Atlas of Galaxies (Sandage 1961). The tidal heating has not destroyed the disk. Its surface brightness can still be fitted by an exponential with roughly the same radial scale length. However, the vertical velocity dispersion has increased dramatically, and as a result the vertical scale height has increased by a factor of 2.

Figure 5 illustrates how the tidal heating causes secular change of the disk thickness. The three lower panels show the factor by which the disk scale height z_0 increases relative to its initial value. The stability of thin disks is also affected by the numerical 'relaxation' effects. Because the number of particles representing the disk is smaller than the actual number of stars, the effect of the particle–particle interactions is stronger than it should be and leads to an artificially fast relaxation. The upper panel shows that the disk thickness increases linearly with time in the absence of any external perturbations. However, since this growth is so steady, it

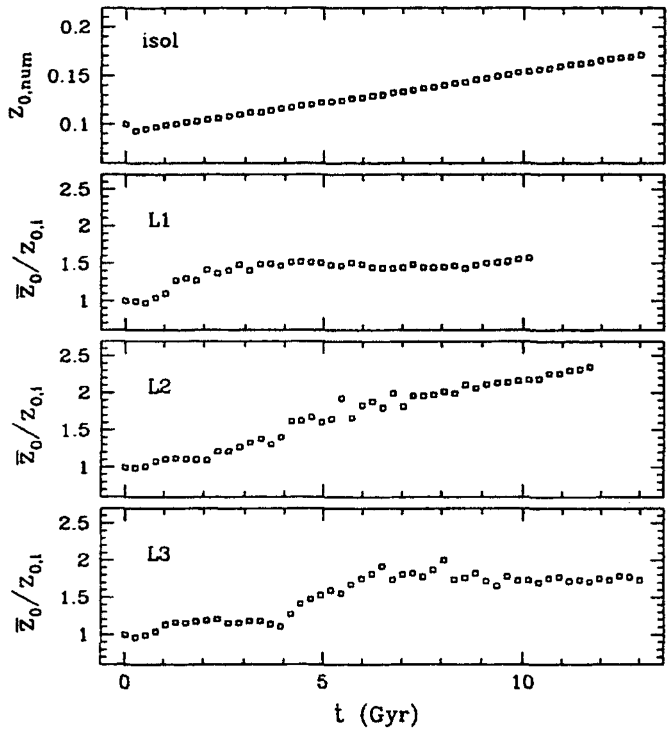

Figure 5 Variation of the disk scale height, z_0, with time for the large galaxies L1, L2, L3 from the three cluster models, and for the test run in isolation. In the three lower panels, the instantaneous value of the scale height is normalized to the initial value and the effect of numerical relaxation is subtracted.

can be corrected for in the later simulations. The resulting quantity, $\bar{z}_0$, measures the real thickening of the disk by the external tidal heating. Panels L1–L3 of Figure 5 refer to the Milky Way-type galaxies in the three cluster models. In each model galactic disks thicken on average by a factor of two, while the effect is noticeably stronger in the low Ω_0 models.

As a result of the vertical thickening and the increased stellar velocity dispersion, the disk of the galaxy becomes stable to any gravitational perturbations. It is unlikely to form any spiral structure and to sustain any significant star formation. Thus, an initially active spiral galaxy would transform into a thick disk galaxy populated by old stars. This is an S0 galaxy, just like NGC 4762 on Figure 4.

Tidal heating accumulates with time. Since the stars are unable to dissipate their 'heat', the disk would eventually become thicker and thicker until it is no longer a disk but an elliptical galaxy. The question is only how long the galaxies experience this tidal metamorphosis. The simulations show that in the Virgo-type clusters spirals can transform into S0 galaxies, but not into ellipticals. In more massive clusters the effect would be stronger. Also, since the magnitude of the tidal effects is determined by the epoch of cluster formation, the heating is stronger in the low Ω_0 models.

The results of these simulations can be extended analytically to other cluster and galactic models. Using Poisson's equation, we can relate the external force to a critical tidal density,

$$\nabla^2 \Phi_{\text{ext}} = 4\pi G \rho_{cr}.$$

This is equivalent to a Roche lobe density in binary stellar systems. A typical value of the tidal force from Figure 3 gives

$$\rho_{\text{cr}} = 1.8 \times 10^{-3} \left(\frac{F_{\text{tid}}}{100\ \text{Gyr}^{-2}} \right) M_\odot\ \text{pc}^{-3}$$

This is to be compared with the average density of galaxies, including their stellar disks and dark matter halos. For the Milky Way-type galaxies, the average density within the radial scale length is $\rho_{\text{av}} \sim 10^{-1} M_\odot$ pc^{-3}, which ensures their central parts are stable. On the other hand, numerous dwarf spheroidal and low surface brightness galaxies have low density, $\rho_{\text{av}}(R_0) \sim 3 \times 10^{-3} M_\odot$ pc^{-3}. These galaxies are dangerously close to destruction and for them tidal effects are very important.

Detailed N-body simulations confirm these expectations. Both the stellar disk and the dark matter halo are disrupted in the low-density galaxies. The stripped stars form long tidal tails and contribute to the diffuse intracluster light, not associated with large luminous galaxies. The dark halos smoothly merge into a single cloud that is now the dark matter halo of the cluster itself.

Still larger contribution to the dark halo of the cluster comes from the partly stripped halos of large galaxies. The luminosity functions of galaxies, both observed and theoretical, indicate that most of the mass is contained in the Milky Way-size galaxies. Once they enter the cluster, their large extended dark matter halos are cut off, as discussed in the beginning of this section. The former halos overlap and merge, leaving the galaxies with a small fraction of their initial mass. This evolution may well explain the small fraction of the mass associated with luminous galaxies in the present-day clusters.

To summarize, dark matter plays a very important role in clusters of galaxies. Through its dominant contribution to gravity on galactic and extragalactic scales, dark matter controls the process of galaxy formation. Through its tidal forces during the hierarchical process of cluster formation, dark matter affects the morphological and dynamical evolution of galaxies.

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