On the Survival and Destruction of Spiral Galaxies in Clusters

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\textbf{ABSTRACT}

We follow the evolution of disk galaxies within a cluster that forms hierarchically in a cold dark matter N-body simulation. At a redshift $z = 0.5$ we select several dark matter halos that have quiet merger histories and are about to enter the newly forming cluster environment. The halos are replaced with equilibrium high resolution model spirals that are constructed to represent examples of low surface brightness (LSB) and high surface brightness (HSB) galaxies. Varying the disk and halo structural parameters reveals that the response of a spiral galaxy to tidal encounters depends primarily on the potential depth of the mass distribution and the disk scale length. LSB galaxies, characterised by slowly rising rotation curves and large scale lengths, evolve dramatically under the influence of rapid encounters with substructure and strong tidal shocks from the global cluster potential – galaxy harassment. We find that up to 90\% of their stars are tidally stripped and congregate in large diffuse tails that trace the orbital path of the galaxy and form the diffuse intra-cluster light. The bound stellar remnants closely resemble the dwarf spheroidals (dE’s) that populate nearby clusters. HSB galaxies are stable to the chaos of cluster formation and tidal encounters. These disks lie well within the tidally limited dark matter halos and their potentials are more concentrated. Although very few stars are stripped, the scale height of the disks increases substantially and no spiral features remain, therefore we speculate that these galaxies would be identified as S0 galaxies in present day clusters.

\textit{Subject headings:} galaxies: clusters, galaxies: interactions, galaxies: evolution, galaxies: halos
1. Introduction

Clusters of galaxies provide a unique environment wherein the galaxy population has been observed to rapidly evolve over the past few billion years (Butcher & Oemler 1978, 1984, Dressler et al. 1998). At a redshift \( z \gtrsim 0.4 \), clusters are dominated by spiral galaxies that are predominantly faint irregular or Sc-Sd types. Some of these spirals have disturbed morphologies; many have high rates of star-formation (Dressler et al. 1994a). Conversely, nearby clusters are almost completely dominated by dwarf spheroidal (dSph,dE), lenticulars (S0) and elliptical galaxies (Bingelli et al. 1987, 1988, Thompson & Gregory 1993). Observations suggest that the elliptical galaxy population was already in place at much higher redshifts, at which time the S0 population in clusters is deficient compared to nearby clusters (Couch et al. 1998, Dressler et al. 1998). This evolution of the morphology-density relation appears to be driven by an increase in the S0 fraction with time and a corresponding decrease in the luminous spiral population.

Low surface brightness (LSB) galaxies appear to avoid regions of high galaxy densities (Bothun et al. 1993, Mo et al. 1994). This is somewhat puzzling since recent work by Mihos et al. (1997) showed that LSB disk galaxies are actually more stable to tidal encounters than HSB disk galaxies. In fact, LSB galaxies have lower disk mass surface densities and higher mass-to-light ratios, therefore their disks are less susceptible to internal global instabilities, such as bar formation. However, in a galaxy cluster, encounters occur frequently and very rapidly, on a shorter timescale than investigated by Mihos et al. and the magnitude of the tidal shocks are potentially very large.

Several physical mechanisms have been proposed that can strongly affect the morphological evolution of disks: ram-pressure stripping (Gunn & Gott 1978), galaxy merging (Icke 1985, Lavery & Henry 1988, 1994) and galaxy harassment (Moore et al. 1996a, 1998). The importance of these mechanisms varies with environment: mergers are frequent in groups but rare in clusters (Ghigna et al. 1998), ram pressure removal of gas is inevitable in rich clusters but will not alter disk morphology (Abadi et al. 1999). The morphological transformation in the dwarf galaxy populations \( (M_b > -16) \) in clusters since \( z = 0.4 \) can be explained by rapid gravitational encounters between galaxies and accreting substructure - galaxy harassment. The impulsive and resonant heating from rapid fly-by interactions causes a transformation from disks to spheroidals.

The numerical simulations of Moore et al. focussed on the evolution of fainter Sc-Sd spirals in static clumpy cluster-like potentials and their transition into dSph’s. In this paper we examine the role of gravitational interactions in driving the evolution of luminous spirals in dense environments. We shall use more realistic simulations that follow the formation and growth of a large cluster that is selected from a cosmological simulation of a critical CDM universe. The parameter space for the cluster model is fairly well constrained once we have adopted hierarchical structure formation. The structure and substructure of virialised clusters is nearly independent of the shape and normalisation of the power spectrum. Clusters that collapse in low Omega universes form earlier, thus their galaxies have undergone more interactions. The cluster that we follow virialises at
\( z \sim 0.3 \), leaving about 4 Gyrs for the cluster galaxies to dynamically evolve.

The parameter space for the model spirals is much larger. Mihos et al. examined the effects of a single encounter at a fixed number of disk scale lengths, whilst varying the disk surface brightness and keeping other properties fixed. The key parameter that determines whether or not dark matter halos survive within a cluster N-body simulation is the core radius of the substructure, which is typically dictated by the softening length (Moore et al. 1996b). We suspect that this may also be a key factor that governs whether or not a given disk galaxy will survive within a dense environment. Most LSB galaxies have slowly rising rotation curves indicating “soft” central potentials and thus should be more unstable than HSB galaxies with flat rotation curves. To investigate this hypothesis we constructed several different galaxy models. A “typical” luminous HSB and LSB disk galaxy that both lie on the same point in the Tully-Fisher relation, as well as a sequence of models that have different surface brightness, disk scale lengths and halo structural parameters.

In Section 2 we examine the response of three different model disk galaxies to a single strong tidal encounter. Section 3 discusses the cosmological simulations in which we follow the hierarchical evolution of the mass distribution. In Section 4 we isolate the properties that determine the stability or instability of disk galaxies orbiting within a cluster and summarise our results in Section 5.

2. The response to strong impulsive encounters

For a given orbit through a cluster, the visible response of a disk galaxy to a tidal encounter depends primarily upon its internal dynamical timescale. Galaxies with cuspy central mass distributions, such as ellipticals, have short orbital timescales at their centres and they will respond adiabatically to tidal perturbations. Sa-Sb spirals have flat rotation curves, therefore a tidal encounter will cause an impulsive disturbance to a distance \( \sim v_c b/V \) from its centre, where \( b \) is the impact parameter, \( V \) is the encounter velocity and \( v_c \) is the galaxy’s rotation speed. LSB galaxies and Sc-Sd galaxies have slowly rising rotation curves, indicating that the central regions are close to a uniform density. The central dynamical timescales are constant throughout the inner disk and an encounter that is impulsive at the core radius will be impulsive throughout the galaxy.

Galaxy-galaxy encounters within a virialised cluster occurs at a relative velocity \( \sim \sqrt{2}\sigma_{1d} \). Substituting parameters for an Sa–Sb galaxy, such as the Milky Way, orbiting within a cluster we find that such encounters will not perturb the disk within \( \sim 3r_d = 10 \) kpc. However, tidal shocks from the mean cluster field also provides a significant heating source for those galaxies on eccentric orbits (Byrd & Valtonen 1990, Valluri 1993, Moore et al. 1996a). Ghigna et al. (1998) studied the orbits of several hundred dark halos within a cluster that formed hierarchically in a cold dark matter universe. The median ratio of apocenter to pericenter was 6:1, with a distribution
skewed towards radial orbits. More than 20% of the halos were on orbits more radial than 10:1. A galaxy on this orbit would move past pericenter at several thousand km s$^{-1}$ and would be heated across the entire disk. We shall examine the response of a disk to a single impulse encounter using N-body simulations.

2.1. The model spiral galaxies

We use the technique developed by Hernquist (1989) to construct equilibrium spiral galaxies with disk, bulge and halo components, designed to represent “standard” HSB and LSB disk galaxies. All the model galaxies investigated in this paper have rotation curves that peak at 200 km s$^{-1}$ and would therefore be a little less luminous than “$L_*$” spirals. Each model has an exponential disk with scale length $r_d = 3$ kpc or $r_d = 7$ kpc and a scale height $r_z = 0.1r_d$. The disks are all constructed using 20,000 star particles and are are stable with a Toomre “Q” parameter of 1.5. Each galaxy has a dark matter halo constructed using 50,000 particles distributed as a modified isothermal sphere with core radius, $r_h = 1.5$ kpc or $r_h = 10$ kpc. (Here, $r_h$ is the radius at which the contribution to the rotation curve is 0.7 times the peak contribution.) One of the “HSB” model galaxies has a small bulge with mass 25% of the disk mass.

To examine the effect of a single impulsive tidal encounter we constructed three separate model galaxies. We have specifically constructed two of these model galaxies so that they both lie at the same point on the Tully-Fisher relation, yet the galaxies will have different internal mass distributions (Zwaan et al. 1995, de Blok & McGaugh 1997). Figure 1 shows the contribution to the rotation velocity of the disks from each component. The galaxy in Figure 1(a) has a concentrated mass distribution as indicated by the flat rotation curve. Note that the bulge component of the HSB galaxy has ensured that the rotation curve is close to flat over the inner 7 disk scale lengths, and is fairly typical of the mass distribution of HSB galaxies (Persic & Salucci 1997). The galaxy in Figure 1(b) has a larger disk scale length and a rotation curve that rises slowly in the central region, typical of that measured for LSB galaxies (de Blok & McGaugh 1996, de Blok & McGaugh 1997).

Although some giant LSB galaxies have a bulge component, their rotation curves still rise slowly. For example, 3 of the 4 LSB galaxies observed by Pickering et al. (1997), with $v_c \geq 200$ km s$^{-1}$ (NGC 7589, F586-6 and Malin 1) all have rotation curves that rise more slowly than than our standard example in Figure 1b. However, in Section 4 we also study the case of extended LSB disks in more concentrated potentials. Giant LSB galaxies also have disk scale lengths $\sim 10-20$ kpc (e.g. Figure 9 of Zwaan et al.), larger than the conservative value we adopt here. We shall see later that galaxies with larger scale lengths are more unstable to disruption and transformation to dSph.

Our model galaxies are somewhat different to those used by Mihos et al. (1997), who kept
the scale lengths constant and only varied the disk mass surface density. In order to examine the effects of surface density we construct a third “LSB” model with a disk 1/8th of the mass of the previous model as shown in Figure 1(b). The HSB model and two LSB models have disk masses of $4 \times 10^{10} M_\odot$, $4 \times 10^{10} M_\odot$ and $5 \times 10^9 M_\odot$ respectively. Adopting a B band mass to light ratio of 2, the central surface brightness of the HSB galaxy is 20.6 mags arcsec$^{-2}$, whilst that of the LSB models are 22.5 and 25.7 mags arcsec$^{-2}$.

The force softening is $0.1 r_d$ for the star particles and $0.3 r_h$ for the halo particles. Their disks are stable and they remain in equilibrium when simulated in isolation. Discreteness in the halo particles causes the disk scale height to increase with time as quantified in Section 3 for the HSB galaxy. This increase is consistent with analytic calculations from Lacey & Ostriker (1988).

We illustrate the effect of a single impulsive encounter on each of our model disks in Figures 2, 3 and 4. At time $t=0$ we send a perturbing halo of mass $2 \times 10^{12} M_\odot$ perpendicular to the plane of the disk at an impact parameter of 60 kpc and velocity of 1500 km s$^{-1}$. This encounter would be typical of that occurring in a rich cluster with a tidally truncated $L_*$ elliptical galaxy near the cluster core. Any one galaxy in the cluster will suffer several encounters stronger than this since the cluster formed. Although we simulate a perpendicular orbit here, we do not expect the encounter geometry to make a significant difference since the difference between direct and retrograde encounters will be relatively small i.e. $V >> v_c$.

At $t=0.1$ Gyrs after the encounter, the perturber has moved 150 kpc away, yet a visible disturbance in the disk is hardly apparent. After 0.2 Gyrs, we can begin to see the response to the tidal shock as material is torn from the disk into extended tidal arms. Even at this epoch there is a clear difference to the response of the perturbation by the HSB and LSB galaxies. After 0.4 Gyrs, the LSB galaxies are dramatically altered over their entire disks and a substantial fraction of material has been removed past their tidal radii. Remarkably, the central disk of the HSB galaxy remains intact and only the outermost stars have been strongly perturbed. A Gyr after the encounter the HSB disk remains stable whereas the LSB disks are highly distorted. The model with the more massive disk has undergone a strong bar instability. The second LSB model with a lighter disk responds in a similar fashion. The disk undergoes strong distortions from the encounter and the same amount of material is tidally removed. However, the lower mass surface density of this disk has suppressed the bar instability, confirming the results of Mihos et al. (1997).

3. Simulating disk evolution within a hierarchical universe

Previous simulations of tidal shocks and galaxy harassment focussed upon the evolution of disk galaxies in static clusters with substructure represented by softened potentials with masses drawn from a Schechter function (Moore et al. 1996a & 1998). We shall use a more realistic approach of treating the perturbations by following the growth of a cluster within a hierarchical
Fig. 1.— The curves show the contributions from stars and dark matter to the total rotational velocity of the disk within (a) the HSB galaxy and (b) the two LSB galaxies, one with a less massive disk but with the same peak rotational velocity.
Fig. 2.— Snapshots of the distribution of disk stars from a HSB galaxy after a single high-speed encounter with a massive galaxy. Each frame is 120 kpc on a side and encounter takes place perpendicular to the disk at the box edge (60 kpc).
Fig. 3.— Snapshots of the distribution of disk stars from the LSB galaxy with a heavy disk (A in Figure 1b) after a single high-speed encounter with a massive galaxy. Each frame is 120 kpc on a side and the encounter takes place perpendicular to the disk at the box edge (60 kpc).
Fig. 4.— Snapshots of the distribution of disk stars from the LSB galaxy with a light disk (B in Figure 1b) after a single high-speed encounter with a massive galaxy. Each frame is 120 kpc on a side and the encounter takes place perpendicular to the disk at the box edge (60 kpc).
cosmological model. The cluster was extracted from a large CDM simulation of a critical universe within a 50 Mpc box and was chosen to be virialised by the present epoch. (We assume a Hubble constant of $100 \, \text{km s}^{-1} \, \text{Mpc}^{-1}$.) Within the turn-around region there are $\sim 10^5$ CDM particles of mass $10^{10} M_\odot$ and their softening length is 10 kpc. At a redshift $z = 0$ the cluster has a one dimensional velocity dispersion of 700 km s$^{-1}$ and a virial radius of 2 Mpc. The tidal field from the mass distribution beyond the cluster’s turn-around radius is simulated with massive particles to speed the computation. (The cluster used here is a low resolution version of the cluster analysed in Ghigna et al. .)

Our aim is to select dark matter halos that are likely to host spiral galaxies and that enter the cluster as it is forming. These halos will be replaced with the high resolution, stable models and the simulation continued to the present epoch. A similar technique was used recently by Dubinski (1998) in order to study the formation of central cluster galaxies. We use the parallel treecode PKDGRAV (Stadel et al. 1998) that has periodic boundary conditions, accurate force resolution and a multi-stepping algorithm. This is vital in this simulation since we must obtain the correct dynamics on sub-kpc scales in a galaxy that is feeling the gravitational tidal field from regions several megaparsecs away.

There are several possible sources of artificial heating that arise from finite timestepping and artificially large dark matter particle masses. Other numerical problems include artificial disk heating by the general background of particles and the dissolution of small scale substructure by the tidal shocks, low resolution and force softening.

### 3.1. Timestepping, resolution and particle discreteness

In order to model the dynamics of star particles within the disk and the growth of the cluster at the same time an efficient multi-stepping algorithm is needed. Most of the particles in the cosmological volume have larger softening and lower velocities than the high resolution galaxy, therefore a fixed timestep would be inefficient. The softening length for star particles in the disk of the model HSB galaxy is $\sim 200$ pc, whilst the CDM particles in the main cluster have 10 kpc softening. At relative velocities of several thousand km s$^{-1}$, some particles require timesteps of order $\sim 10^5$ years and thus require more than 50,000 steps in total. The multisteping criteria of PKDGRAV is based on the local acceleration, therefore it is better suited for following encounters than is a velocity criteria. Furthermore, a velocity criteria is inefficient for circular orbits within isothermal potentials since all the disk particles would be on the same timestep regardless of their local density. To test the multisteping and accuracy of the force calculation, we placed the model galaxy in a void, 10 Mpc away from the forming cluster at $z=0.5$. The galaxy evolved in relative isolation for half a Hubble time, yet remained very stable, although the disk scale height increases slowly due to discreteness as quantified in Figure 4. Even with 50,000 halo particles within 10 disk scale lengths, the disk vertical scale height more than doubled over the 5 Gyr integration.
Fig. 5.— The vertical scale height, $r_z$, of the disk in units of the initial disk scale length, $r_d$, measure at $r_d$ plotted against time. The circles are data for the HSB galaxy placed in a void. The squares and triangles show one of the HSB and LSB galaxies respectively, that enters the cluster at $z=0.5$. 
A long standing problem in “low-resolution” dissipationless N-body simulations is the dissolution of substructure. When large cosmological volumes are simulated, virialised halos with less than $\lesssim 10^5$ particles contain very little substructure. This is due to tidal shocks disrupting the heavily softened halos that fall into larger systems (Moore et al. 1996b). The absence of halos-within-halos will artificially reduce the effects of harassment in our simulation since the full mass spectrum of perturbing clumps will not be present. However, harassment is dominated by the effects of several strong encounters with large halos of mass $\gtrsim L_* \equiv v_c = 220 \text{ km s}^{-1}$. All halos more massive than this are resolved by our simulation outside of the cluster, and some fraction will survive for at least a crossing time within the cluster.

At the final time within the cluster’s virial radius there are just 6 surviving substructure halos with circular velocities larger than 220 km s$^{-1}$. (N.B. When this cluster was simulated with $\sim 10^6$ dark matter particles and 5 kpc softening, we found 17 halos with $v_c \gtrsim 220 \text{ km s}^{-1}$ within the virial radius.) We find that the chaos of cluster formation is the time when most damage is caused to the disk galaxies. At a redshift $z \sim 0.5$ many smaller halos are streaming together along filaments at high velocities - encounters with these halos wreak havoc with the disks of LSB galaxies, and including the subsequent encounters with galaxies within the cluster will only add to the disk heating. In agreement with the analysis of Ghigna et al., none of the galaxies suffer a single merger whilst orbiting within the cluster.

### 3.2. Results

Between a redshift $z=2$ to $z=0.5$ we follow the merger histories of several candidate dark matter halos from the cosmological simulation that end up within the cluster at later times. We select three halos with circular velocities $\sim 200 \text{ km s}^{-1}$ that have suffered very little merging over this period and would therefore be most likely to host disk galaxies. We extract these halos from the simulation at $z=0.5$ and replace the entire halo with the pre-built high resolution model galaxies. We rescale the disk and halo scale lengths by $(1 + z)^{-1}$ according to the prescription of Mao et al. (1998) to represent the galaxies entering the cluster at higher redshifts. This theoretical prescription is based on modeling disk formation within a hierarchical universe. Although observational evidence for this behaviour is lacking (Lilly et al. 1998), it will only serve to make disks at higher redshifts more stable to harassment.

On a 64 node parallel computer, each run takes several hours; three runs were performed in which the halos were replaced with the HSB disks and a further six runs using the LSB disks from Figure 1. Figure 6 shows the results of one of the LSB simulations from a redshift $z=0.5$ to the present day - this evolution is typical of all six runs. The colours show the local density of CDM particles on a scale of $10 - 10^6 \rho_{\text{crit}}$ and the size of each image is a comoving 10 Mpc. At $z=0.5$, the cluster is only just starting to form from a series of mergers of several individual group and galaxy
sized halos - the small halo that we have replaced with an LSB galaxy at $z=0.5$ is highlighted in the first two images. The green points show the stars within the stellar disk that are barely visible on this scale. The cluster quickly virialises, although several dark matter clumps survive the collapse and remain intact orbiting within the clusters virial radius. Between $z = 0.4 - 0.3$ the model galaxy receives a series of large “tidal shocks” from the halos that are assembling the cluster.

Once the galaxy enters the virialised cluster, it continues to suffer encounters with infalling and orbiting substructure. By a redshift $z=0.1$, most of the stars have been stripped from the disk and now orbit through the cluster - closely following the rosette orbit of the parent galaxy. The final orbit of this run has apocenter of 1000 kpc and pericenter of 150 kpc. Of the LSB galaxy runs, between 50% and 90% of the stars were harassed from the disk, whereas the stellar mass loss in the HSB runs was between 1% and 10%. We find no discernable difference between the stellar mass loss or the kinematical remnants of the two different LSB models in Figure 1(b). The tidal encounters are so strong and frequent that the additional stability provided by a dark matter dominated disk is not apparent.

3.3. The final stellar states

Only three different orbital realisations of each LSB model were carried out, therefore we cannot comment on correlations between properties, but some general remarks about the kinematics of the stellar remnants can be made. The final stellar systems are prolate, with shapes supported by velocity anisotropy, similar to the remnants of harassed Sc-Sd galaxies analysed in Moore et al. (1998). Figure 7(a) shows the initial and final surface density of stars from the LSB galaxy. Within $\sim 5$ kpc, the remnants are well fitted by exponentials with scale lengths in the range $\sim 1.5 - 2.5$ kpc, a significant decrease from their initial values. Even though 50-90% of the stars have been tidally stripped, the central surface brightness increases by up to 2 magnitudes. This increase in the central stellar density results from an increase in the random motions of stars by the heat input from harassment - phase space density is conserved. The dark matter particles are initially on more radial orbits than the disk stars, therefore they can be stripped from deeper within the potential halo if they are caught at apocenter. This results in a larger fraction of dark matter being removed, even from within the optical extent of the galaxies and the final stellar mass to dark matter ratios decrease from 16 to $\sim 2 - 5$.

Tidal stripping combined with the additional fading from several Gyrs of stellar evolution will leave the remnants faint and diffuse. Combining these results with our simulations of fainter Sc-Sd galaxies in clusters, we expect that the luminosity function of dwarf spheroidals (dSph - frequently called dE’s) in clusters should reflect the luminosity function of bulgeless Sc-Sd spirals and LSB galaxies that have entered the cluster. Therefore, if a substantial population of luminous
Fig. 6.— Snapshots of the particle distribution within a comoving 10 Mpc box centered on the forming cluster. The redshifts of each frame are indicated. The colors show the local density of dark matter on a scale of $1 - 10^6$ times the mean density. The green particles are the star particles from the disk of the high resolution model galaxy. Initially the stars are confined to the disk, but at $z=0$ they are spread along the orbital path of the galaxy which has apocenter of 1000 kpc and pericenter of 250 kpc. The clusters virial radius at $z=0$ is $\sim 2$ Mpc.
Fig. 7.— The open circles show the initial surface density of disk stars in (a) the LSB model galaxy and (b) the HSB model galaxy. The open circles show the surface density at the final time after evolving within the cluster. The solid lines show exponential disk fits with the indicated scale lengths.
LSB galaxies exist, we should find their post-genitors in clusters as a large population of diffuse low luminosity spheroidals with low mass to light ratios.

The evolution of the HSB models contrasts sharply with the LSB models. These galaxies lose only a small fraction of their stars and they remain in a disk configuration. The scale height of their disks increases by a factor of 2-4 over that sustained by discreteness effects. The increase in the stellar velocity dispersion also leads to a small increase in the central surface brightness by about half a magnitude (see Figure 7(b)). Within about 10 kpc the disks are well fitted by exponentials with scale lengths that are slightly smaller by $\sim 20\%$ than their initial values. Beyond this region we find an excess in surface brightness over a single exponential disk fit; at 20 kpc this is over one magnitude. The final disks do not have any obvious spiral features and if the gas is removed via ram-pressure stripping, we speculate that these galaxies would be identified as S0 galaxies in present day clusters.

4. What determines the stability or instability of disks in clusters?

The parameters for the “typical” HSB and LSB galaxies that we constructed are different in many aspects. It is not clear which parameter, or combination of them maintains the stability of the HSB galaxy. We performed a series of tests to isolate the effects of the three important structural parameters; the surface mass density of the disk, the disk scale length and the depth of the potential well provided by a dark halo. (A prominent stellar bulge will have a similar effect as a dark matter halo with a very small core radius.)

We construct 7 model galaxies that have equilibrium disk + halo components. The disks have scale lengths of either 3 kpc or 7 kpc and a dark halo with core radius 1 kpc or 10 kpc which provides a peak rotational velocity of 200 km s$^{-1}$. All possible combinations of these parameters yield 4 models and we construct a further 3 models in which we vary only the disk mass. The model parameters are summarised in Table 1. The contribution to the rotation curve $v_c = \sqrt{GM/r}$ of the halo and stellar components of each model are plotted in Figure 8. The entire simulation is re-run seven times with each model on the same orbit, thus they suffer identical harassment histories within the cluster. The dashed and dotted curves in Figure 8 show the final rotation curves of the stellar and halo components of all seven models.

The standard lore is that LSB disks inhabit low density halos (rising rotation curves) and HSB disks live in concentrated halos (flat rotation curves). These models would correspond to A and F respectively in Table 1; their final mass distributions are plotted in Figure 8(a) and 8(b). The behaviour of these models is similar to the two “standard” models discussed in the previous section.

We know that a disk is highly unstable to mass loss, disruption and morphological transformation if both the halo core radius and disk scale lengths are large. Which parameter is
Fig. 8.— The contribution of the stars and dark matter to the rotational velocity of the seven test galaxies, all plotted in physical coordinates. The initial mass distributions are shown by the solid curves whilst the final mass distributions are shown as dotted or dashed curves. The long dashed and dotted curves in panel (a) show the halo and disk distributions respectively at the final time. The other galaxies in panels (b)-(d) lose much less mass and it should be relatively clear which component the broken curves represent at the final time.
most important? The answer is that they both are. From Table 1 we can see that a galaxy with a scale length of 3 kpc is stable against mass loss independent of the halo core radii, although their final disk scale heights are significantly higher in the case of an extended halo. Furthermore, an extended disk that was highly unstable in a soft potential can be stabilised in a concentrated potential, although they suffer significant mass loss and large amounts of internal heating.

The core radius of the mass distribution makes a large difference in the extent of the final mass distribution. Models with \( r_h = 10 \) kpc and \( r_h = 1 \) kpc (with the small disk), had final tidally limited radii of \( \sim 30 \) kpc and 50 kpc.

Models B C and D are identical except for their disk mass which vary by a factor of eight. The stellar and dark matter mass loss is very similar between all these models and we cannot find any significant distinguishing feature between the final stellar systems. Although the disks lose over a fifth of their mass, the final objects are rotationally supported but suffer a lot of heating. Within a disk scale length, the initial and final surface density profiles are similar to the initial conditions, although model C ends up slightly more concentrated than model D. The deeper potentials have stopped the transformation in dSph galaxies but the remaining disks have large scale heights (\( \gtrsim 2 \) kpc) and they all look like extremely puffed up low surface brightness S0 galaxies.

5. Summary and discussion

We have identified halos within a cosmological simulation that have quiet merger histories and that enter a cluster environment at a redshift \( z = 0.5 \). At this epoch we replace the halos with high resolution model spiral galaxies with either LSB or HSB disks and continue the simulation to the present day. This technique is a simple and powerful tool for studying the morphological evolution of galaxies in different environments.

The response of a disk galaxy to tidal shocks is governed primarily by the concentration of the mass distribution that encompasses it and the disk scale length. LSB galaxies have slowly rising rotation curves, large disk scale lengths and they cannot survive the chaos of cluster formation; gravitational tidal shocks from the merging substructure literally tear these systems apart, leaving their stars orbiting freely within the cluster and providing the origin of the intra-cluster light.

Recent observations of individual planetary nebulae within clusters, but outside of galaxies, lends support to this scenario. Estimates of the total diffuse light within clusters, using CCD photometry (Bernstein \textit{et al.} 1995, Tyson & Fischer 1995) or the statistics of intra-cluster stars (Theuns & Warren 1997, Feldmeier \textit{et al.} 1998, Mendez \textit{et al.} 1998, Ferguson \textit{et al.} 1998), ranges from 10\% to 45\% of the light attached to galaxies. Presumably, these stars must have originated within galactic systems. The integrated light within LSB galaxies may be equivalent to the light within “normal” spirals (Bothun, Impey & McGaugh 1997, and references within). This is consistent with the entire diffuse light in clusters originating from harassed LSB galaxies.
Models for the formation of LSB galaxies typically assume that they form within dark matter halos with high spin parameters (Dalcanton et al. 1997, Jiminez et al. 1998). Recent work by Lemson & Kauffmann (1998) demonstrates that the properties of dark matter halos, including spin parameter, are independent of environment. Therefore, the initial distribution of LSB galaxies should be unbiased with respect to the local overdensity, and the quantity of intra-cluster light within clusters may provide an upper limit to the maximum amount of light that can exist in LSB galaxies in the universe.

High surface brightness disk galaxies and galaxies with luminous bulges have steep mass profiles that give rise to flat rotation curves over their visible extent. The orbital time within a couple of disk scale lengths is short enough for the disk to respond adiabatically to rapid encounters. Tidal shocks cannot remove a large amount of material from these galaxies, nor transform them between morphological types, but will heat the disks and drive instabilities that can funnel gas into the central regions (Lake et al. 1998, Gnedin 1999). A few Gyrs after entering a cluster, their disks are thickened and no spiral features remain. If ram-pressure is efficient at removing gas from disks, we speculate that these galaxies will evolve into S0’s. Since the harassment process and ram-pressure stripping are both more effective near the cluster centers, we expect that a combination of these effects may drive the morphology–density relation within clusters.

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Table 1: Models to test disk stability as a function of potential depth and disk structure. Columns 2 and 3 are the disk scale lengths and halo core radii, column 4 gives the dark to stellar mass ratio within 30 kpc and columns 5 and 6 show the percentage of stars and dark matter that are stripped from within a radius of 30 kpc by the final time.

| Model | $r_d$ (kpc) | $r_h$ (kpc) | $M_{halo}/M_{disk} < 30$ kpc | stars | dark matter |
|-------|-------------|-------------|-----------------------------|-------|-------------|
| A     | 7           | 10          | 16                          | 57%   | 92%         |
| B     | 7           | 1           | 16                          | 23%   | 40%         |
| C     | 7           | 1           | 7                           | 20%   | 35%         |
| D     | 7           | 1           | 57                          | 22%   | 41%         |
| E     | 3           | 10          | 16                          | 1%    | 93%         |
| F     | 3           | 1           | 16                          | 1%    | 35%         |
| G     | 3           | 10          | 57                          | 2%    | 60%         |

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