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On the survival and destruction of spiral galaxies in clusters

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ABSTRACT

We follow the evolution of disc 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 haloes that have quiet merger histories and are about to enter the newly forming cluster environment. The haloes 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 disc and halo structural parameters reveals that the response of a spiral galaxy to tidal encounters depends primarily on the potential depth of its mass distribution and the disc scalelength. LSB galaxies, characterized by slowly rising rotation curves and large scalelengths, 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 per cent of their stars are tidally stripped, and congregate in large diffuse tails that trace the orbital path of the galaxy and form the diffuse intracluster light. The bound stellar remnants closely resemble the dwarf spheroidals (dEs) that populate nearby clusters. HSB galaxies are stable to the chaos of cluster formation and tidal encounters. These discs lie well within the tidally limited dark matter haloes, and their potentials are more concentrated. Although very few stars are stripped, the scaleheight of the discs increases substantially and no spiral features remain; we therefore speculate that these galaxies would be identified as S0 galaxies in present-day clusters.

Key words: galaxies: clusters: general – galaxies: evolution – galaxies: haloes – galaxies: interactions – galaxies: spiral.

1 INTRODUCTION

Clusters of galaxies provide a unique environment wherein the galaxy population has been observed to evolve rapidly 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. 1994). Conversely, nearby clusters are almost completely dominated by dwarf spheroidal (dSph, dE), lenticulars (S0) and elliptical galaxies (Bingelli, Tammann & Sandage 1987; Bingelli, Sandage & Tammann 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, McGaugh & Bothun 1994). This is somewhat puzzling, since recent work by Mihos, McGaugh & de Blok (1997) showed that LSB disc galaxies are actually *more* stable to tidal encounters than HSB disc galaxies. In fact, LSB galaxies have lower disc mass surface densities and higher mass-to-light ratios, and so their discs 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 time-scale 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 discs: ram-pressure stripping (Gunn & Gott 1972), galaxy merging (Icke 1985; Lavery & Henry 1988, 1994) and galaxy harassment (Moore et al. 1996a; Moore, Lake & Katz 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 disc morphology (Abadi et al., in preparation). The morphological transformation in the dwarf galaxy populations ($M_b > -16$) in clusters formed 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 discs to spheroidals.

The numerical simulations of Moore et al. (1996a, 1998) focused on the evolution of fainter Sc–Sd spirals in static clumpy cluster-like potentials and their transition into dSphs. 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 cold dark matter (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 virialized clusters is nearly independent of the shape and normalization of the power spectrum. Clusters that collapse in low-Ω universes form earlier; thus their galaxies have undergone more interactions. The cluster that we follow virializes at $z \sim 0.3$, leaving about 4 Gyr for the cluster galaxies to evolve dynamically.

The parameter space for the model spirals is much larger. Mihos et al. (1997) examined the effects of a single encounter at a fixed number of disc scalelengths, whilst varying the disc surface brightness and keeping other properties fixed. The key parameter that determines whether or not dark matter haloes survive within a cluster *N*-body simulation is the core radius of the substructure, which is typically dictated by the softening length (Moore, Katz & Lake 1996b). We suspect that this may also be a key factor that governs whether or not a given disc 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. 'Typical' luminous HSB and LSB disc galaxies that both lie on the same point in the Tully–Fisher relation, as well as a sequence of models that have different surface brightness, disc scalelengths and halo structural parameters.

In Section 2 we examine the response of three different model disc 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 disc galaxies orbiting within a cluster, and we summarize our results in Section 5.

2 THE RESPONSE TO STRONG IMPULSIVE ENCOUNTERS

For a given orbit through a cluster, the visible response of a disc galaxy to a tidal encounter depends primarily upon its internal dynamical time-scale. Galaxies with cuspy central mass distributions, such as ellipticals, have short orbital time-scales at their centres, and they will respond adiabatically to tidal perturbations. Sa–Sb spirals have flat rotation curves, and so 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 time-scales are constant throughout the inner disc, and an encounter that is impulsive at the core radius will be impulsive throughout the galaxy.

Galaxy–galaxy encounters within a virialized 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 disc within $\sim 3r_d = 10$ kpc. However, tidal shocks from the mean cluster field also provide a significant heating source for those galaxies on eccentric orbits (Byrd & Valtonen 1990; Valluri & Jog 1991; Moore et al. 1996b). Ghigna et al. (1998) studied the orbits of several hundred dark haloes within a cluster that formed hierarchically in a CDM universe. The median ratio of apocentre to pericentre was 6:1, with a distribution skewed towards radial orbits. More than 20 per cent of the haloes were on orbits more radial than 10:1. A galaxy on this orbit would move past pericentre at several thousand km s^{-1}, and would be heated across the entire disc. We shall examine the response of a disc to a single impulse encounter using *N*-body simulations.

2.1 The model spiral galaxies

We use the technique developed by Hernquist (1993) to construct equilibrium spiral galaxies with disc, bulge and halo components, designed to represent 'standard' HSB and LSB disc galaxies. All the model galaxies investigated in this paper have rotation curves that peak at 200km s^{-1}, and would therefore be a little less luminous than 'L_*' spirals. Each model has an exponential disc with scalelength $r_d = 3$ or 7 kpc and a scaleheight $r_z = 0.1r_d$. The discs are all constructed using 20 000 star particles, and 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, $r_h = 1.5$ or 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 per cent of the disc mass.

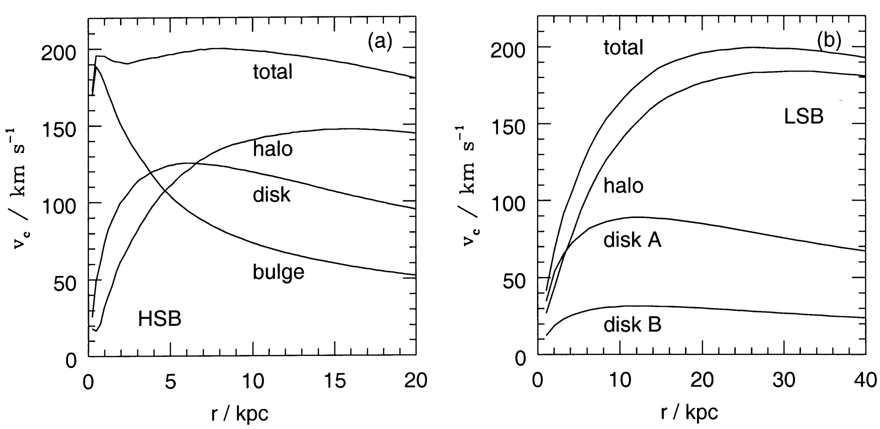

Figure 1. The curves show the contributions from stars and dark matter to the total rotational velocity of the disc within (a) the HSB galaxy and (b) the two LSB galaxies, one with a less massive disc but with the same peak rotational velocity.

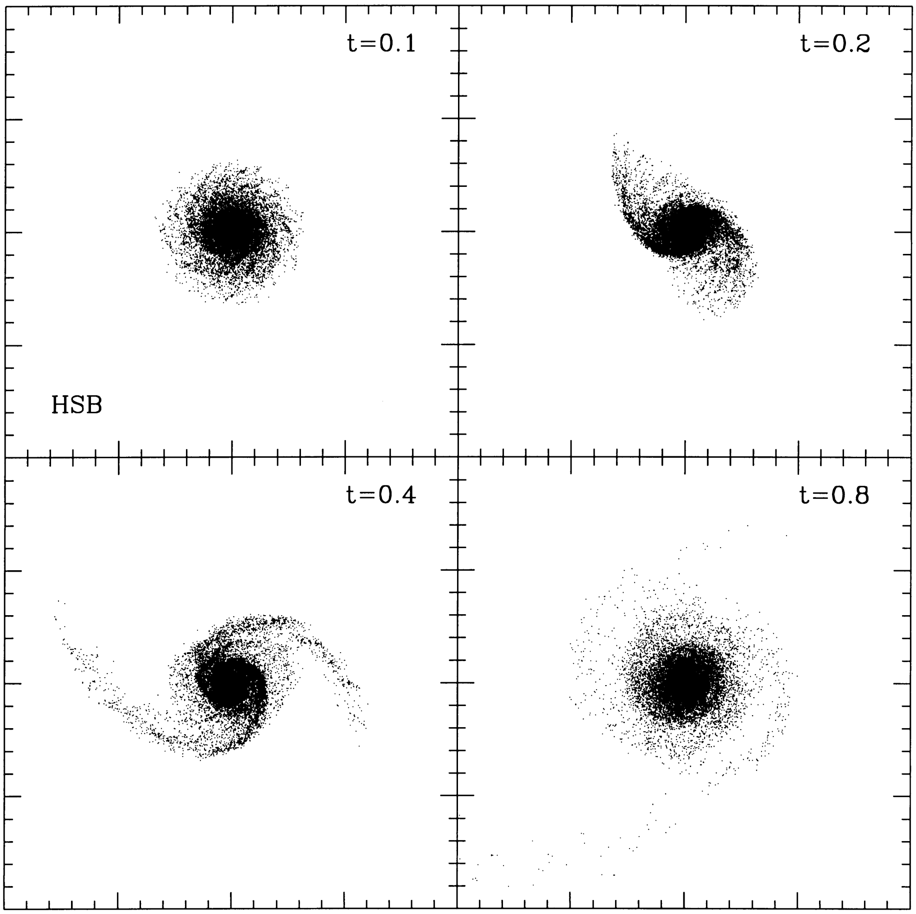

Figure 2. Snapshots of the distribution of disc stars from a HSB galaxy after a single high-speed encounter with a massive galaxy. Each frame is 120 kpc on a side, and the encounter takes place perpendicular to the disc at the box edge (60 kpc). The time unit is Gyr.

To examine the effect of a single impulsive tidal encounter, we constructed three seperate 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). Fig. 1 shows the contribution to the rotation velocity of the discs from each component. The galaxy in Fig. 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 disc scalelengths, and is fairly typical of the mass distribution of HSB galaxies (Persic & Salucci 1997). The galaxy in Fig. 1(b) has a larger disc scalelength and a rotation curve that rises slowly in the central region, typical of that measured for LSB galaxies (de Blok & McGaugh 1996, 1997).

Although some giant LSB galaxies have a bulge component, their rotation curves still rise slowly. For example, three of the four LSB galaxies observed by Pickering et al. (1997), with $v_{\rm c} \gtrsim 200\,{\rm km\,s^{-1}}$ (NGC 7589, F586-6 and Malin 1) all have rotation curves that rise more slowly than than our standard example in Figure 1(b). However, in Section 4 we also study the case of extended LSB discs in more concentrated potentials. Giant LSB galaxies also have disc scalelengths $\sim 10 - 20$ kpc (e.g. fig. 9 of Zwaan et al. 1995), larger than the conservative value we adopt here. We shall see later that galaxies with larger scalelengths are more unstable to disruption and transformation to dSph.

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

The force softening is $0.1r_{\rm d}$ for the star particles and $0.3r_{\rm h}$ for the halo particles. Their discs are stable, and they remain in equilibrium when simulated in isolation. Discreteness in the halo particles causes the disc scaleheight to increase with time as quantified in Section 3 for the HSB galaxy. This increase is consistent with analytic calculations by Lacey & Ostriker (1985).

We illustrate the effect of a single impulsive encounter on each of our model discs in Figs 2, 3 and 4. At time $t = 0$ we send a perturbing halo of mass $2 \times 10^{12}\,{\rm M}_{\odot}$ perpendicular to the plane of the disc at an impact parameter of 60 kpc and a velocity of 1500 ${\rm km\,s^{-1}}$. 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

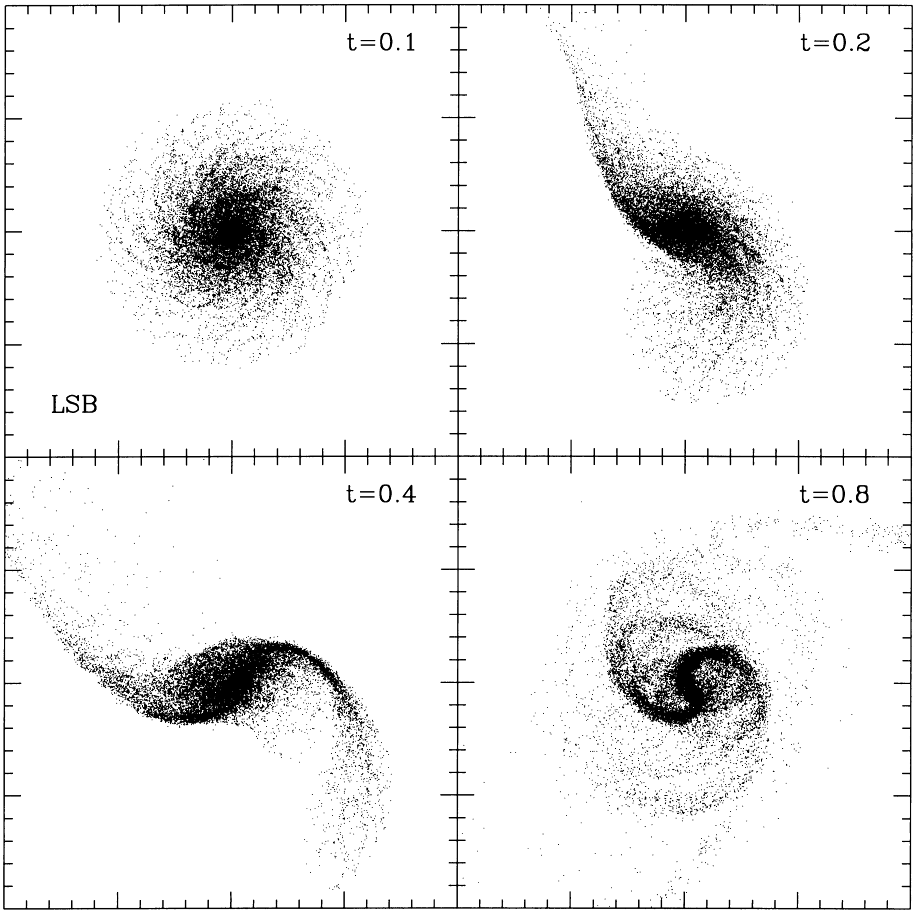

Figure 3. Snapshots of the distribution of disc stars from the LSB galaxy with a heavy disc (A in Fig. 1b) after a single high-speed encounter with a massive galaxy. Each frame is 120 kpc on a side, and the encounter takes place perpendicular to the disc at the box edge (60 kpc).

difference between direct and retrograde encounters will be relatively small, i.e., $V >> v_c$.

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

3 SIMULATING DISC EVOLUTION WITHIN A HIERARCHICAL UNIVERSE

Previous simulations of tidal shocks and galaxy harassment focused upon the evolution of disc 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 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 virialized by the present epoch. (We assume a Hubble constant of $100\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$.) Within the turn-around region there are $\sim 10^5$ CDM particles of mass $10^{10}\,\mathrm{M}_\odot$, and their softening length is 10 kpc. At a redshift $z = 0$ the cluster has a one-dimensional velocity dispersion of $700\,\mathrm{km\,s^{-1}}$ 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 by Ghigna et al. 1998)

Our aim is to select dark matter haloes that are likely to host spiral galaxies and that enter the cluster as it is forming. These haloes 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., in preparation) that has periodic boundary conditions, accurate force resolution and a multistepping algorithm. This is vital in this simulation, since we must obtain the correct dynamics on subkiloparsec scales in a galaxy that is feeling the gravitational tidal field from regions several megaparsecs away.

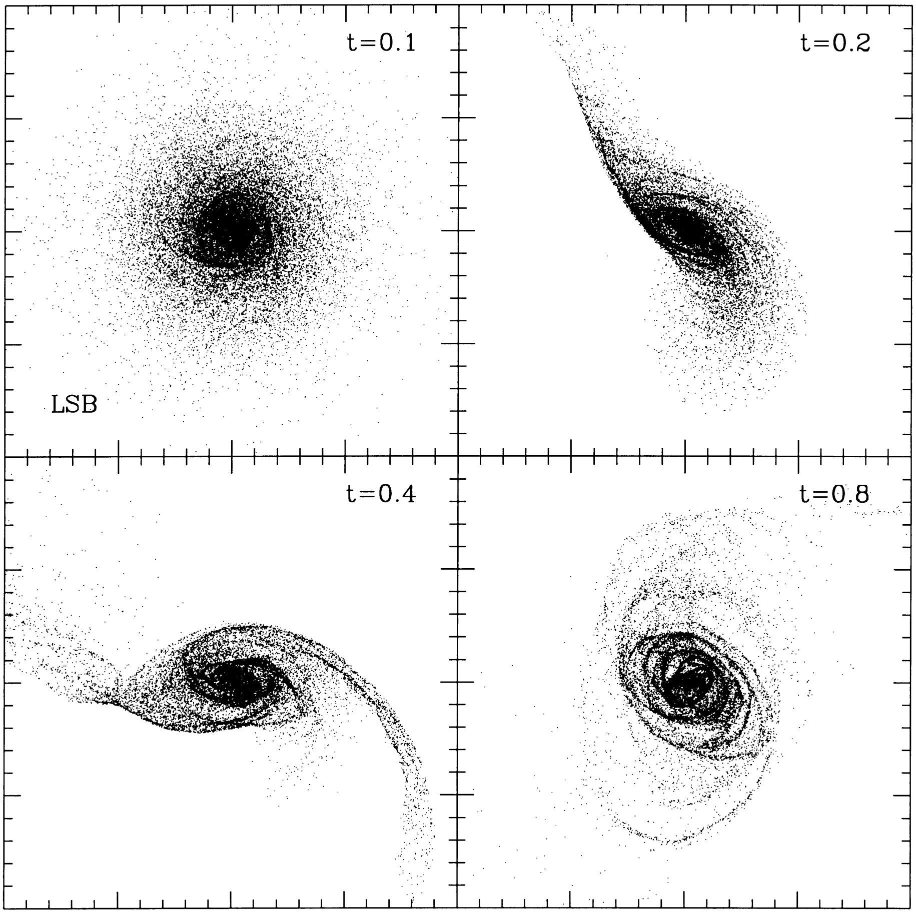

Figure 4. Snapshots of the distribution of disc stars from the LSB galaxy with a light disc (B in Fig. 1b) after a single high-speed encounter with a massive galaxy. Each frame is 120 kpc on a side, and the encounter takes place perpendicular to the disc at the box edge (60 kpc).

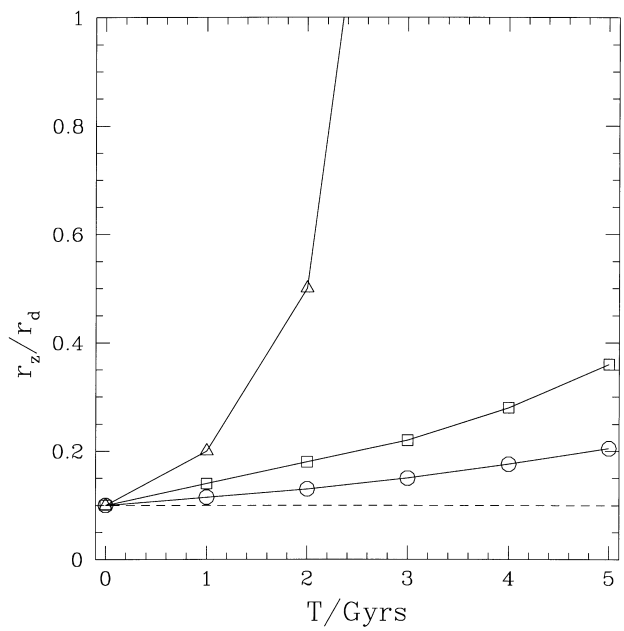

Figure 5. The vertical scaleheight, r_z, of the disc in units of the initial disc scalelength, r_d, measure at r_d plotted against time. The circles are data for the HSB galaxy placed in a void. The squares and triangles show one of the HSB and LSB galaxies respectively, that enters the cluster at $z = 0.5$.

There are several possible sources of artificial heating that arise from finite time-stepping and artificially large dark matter particle masses. Other numerical problems include artificial disc 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 Time-stepping, resolution and particle discreteness

In order to model the dynamics of star particles within the disc and the growth of the cluster at the same time, an efficient multistepping algorithm is needed. Most of the particles in the cosmological volume have larger softening and lower velocities than the high-resolution galaxy, and so a fixed time-step would be inefficient. The softening length for star particles in the disc of the model HSB galaxy is ~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 time-steps of order ~10^5 yr and thus require more than 50 000 steps in total. The multistepping criterion of PKDGRAV is based on the local acceleration, and so it is better suited for following encounters than a velocity criterion. Furthermore, a velocity criterion is inefficient for circular orbits within isothermal potentials, since all the disc particles would be on the same time-step regardless of their local density. To test the multistepping and the 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 disc scaleheight increases slowly due to discreteness, as quantified in Fig. 5. Even with 50 000 halo particles within 10 disc scalelengths, the disc vertical scaleheight more than doubled over the 5-Gyr integration.

A long-standing problem in 'low-resolution' dissipationless *N*-body simulations is the dissolution of substructure. When large cosmological volumes are simulated, virialized haloes with less than $\lesssim 10^5$ particles contain very little substructure. This is due to tidal shocks disrupting the heavily softened haloes that fall into larger systems (Moore et al. 1996b). The absence of haloes-within-haloes 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 haloes of mass $\gtrsim L* \equiv v_c = 220\,\mathrm{km\,s^{-1}}$. All haloes 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 six surviving substructure haloes with circular velocities larger than $220\,\mathrm{km\,s^{-1}}$. (N.B. When this cluster was simulated with $\sim 10^6$ dark matter particles and 5 kpc softening, we found 17 haloes with $v_c \gtrsim 220\,\mathrm{km\,s^{-1}}$ within the virial radius.) We find that the chaos of cluster formation is the time when most damage is caused to the disc galaxies. At a redshift $z \sim 0.5$ many smaller haloes are streaming together along filaments at high velocities – encounters with these haloes wreak havoc with the discs of LSB galaxies, and including the subsequent encounters with galaxies within the cluster will only add to the disc heating. In agreement with the analysis of Ghigna et al. (1998), none of the galaxies suffer a single merger whilst orbiting within the cluster.

3.2 Results

Between a redshift $z = 2$ and 0.5 we follow the merger histories of several candidate dark matter haloes from the cosmological simulation that end up within the cluster at later times. We select three haloes with circular velocities $\sim 200\,\mathrm{km\,s^{-1}}$ that have suffered very little merging over this period and would therefore be most likely to host disc galaxies. We extract these haloes from the simulation at $z = 0.5$ and replace the entire halo with the pre-built high-resolution model galaxies. We rescale the disc and halo scalelengths by $(1+z)^{-1}$ according to the prescription of Mao, Mo & White (1998) to represent the galaxies entering the cluster at higher redshifts. This theoretical prescription is based on modelling disc formation within a hierarchical universe. Although observational evidence for this behaviour is lacking (Lilly et al. 1998), it will only serve to make discs 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 haloes were replaced with the HSB discs, and a further six runs using the LSB discs from Fig. 1. Fig. 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 $10\text{–}10^6\rho_{\mathrm{crit}}$, 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 haloes – 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 disc that are barely visible on this scale. The cluster quickly virializes, although several dark matter clumps survive the collapse and remain intact orbiting within the clusters virial radius. Between $z = 0.4$ and 0.3 the model galaxy receives a series of large 'tidal shocks' from the haloes that are assembling the cluster.

Once the galaxy enters the virialized 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 disc and now orbit through the cluster – closely following the rosette orbit of the parent galaxy. The final orbit of this run has an apocentre of 1000 kpc and a pericentre of 150 kpc. Of the LSB galaxy runs, between 50 and 90 per cent of the stars were harassed from the disc, whereas the stellar mass loss in the HSB runs was between 1 and 10 per cent. We find no discernible difference between the stellar mass loss or the kinematical remnants of the two different LSB models in Fig. 1(b). The tidal encounters are so strong and frequent that the additional stability provided by a dark matter dominated disc is not apparent.

3.3 The final stellar states

Only three different orbital realizations of each LSB model were carried out, and so we cannot comment on correlations between properties; however, 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 by Moore et al. (1998). Fig. 7(a) shows the initial and final surface density of stars from the LSB galaxy. Within ~ 5 kpc, the remnants are well fitted by exponentials with scalelengths in the range $\sim 1.5 - 2.5$ kpc, a significant decrease from their initial values. Even though 50–90 per cent of the stars have been tidally stripped, the central surface brightness increases by up to 2 mag $\mathrm{arcsec^{-2}}$. 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 disc stars, and so they can be stripped from deeper within the potential halo if they are caught at apocentre. 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 Gyr 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 dEs) 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 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 disc configuration. The scaleheight of their discs increases by a factor of 2–4 over that sustained by discreteness effects (cf. Fig. 5). The increase in the stellar velocity dispersion also leads to a small increase in the central surface brightness by about 0.5 mag $\mathrm{arcsec^{-2}}$ (see Fig. 7b). Within about 10 kpc the discs are well fitted by exponentials with scalelengths that are slightly smaller by ~ 20 per cent than their initial values. Beyond this region we find an excess in surface brightness over a single exponential disc fit; at 20 kpc this is over 1 mag $\mathrm{arcsec^{-2}}$. The final discs do not have any obvious spiral features, and if the gas is removed via

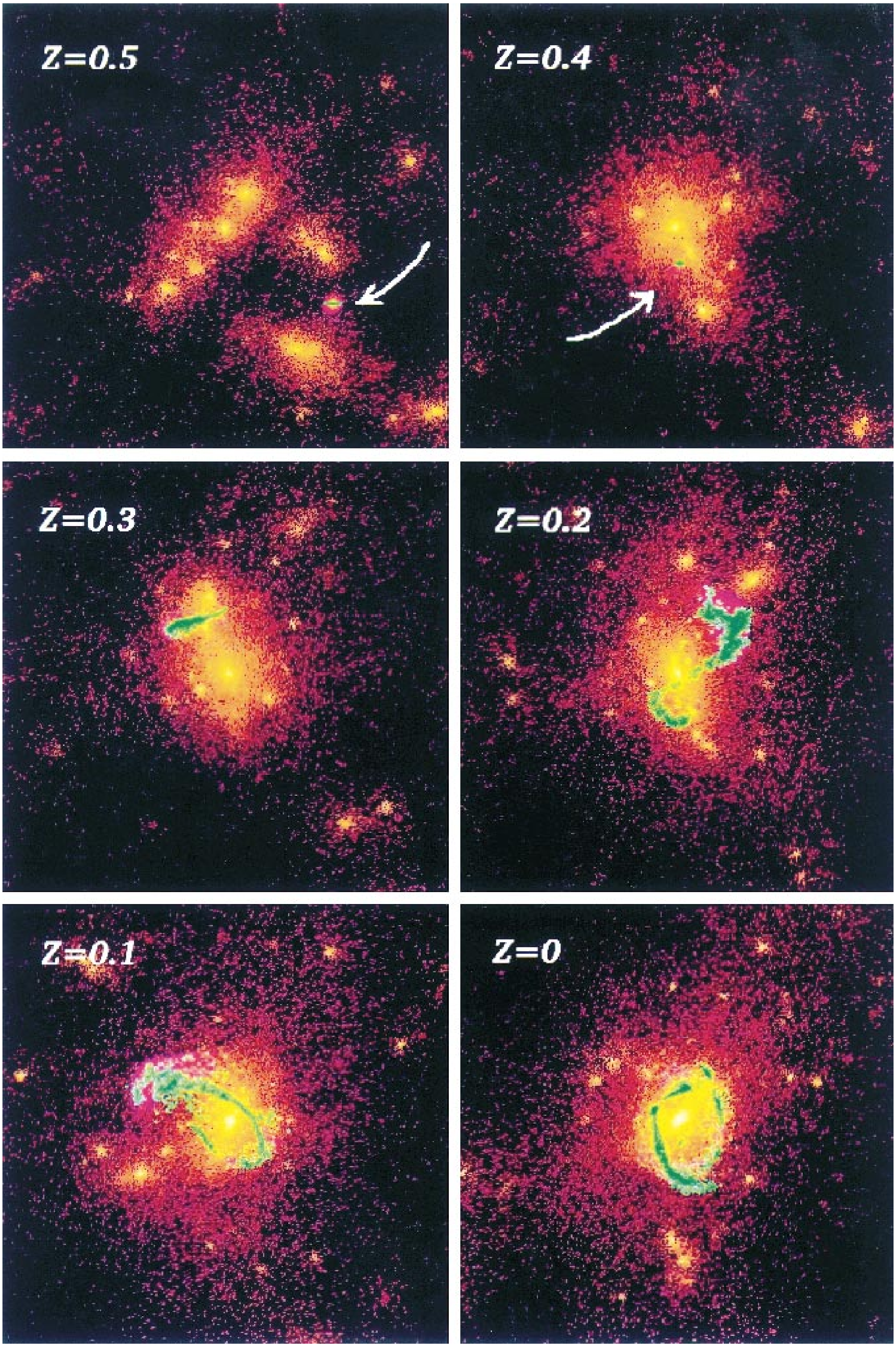

Figure 6. Snapshots of the particle distribution within a comoving 10-Mpc box centred on the forming cluster. The redshifts of each frame are indicated. The colours show the local density of dark matter on a scale of $1-10^6$ times the mean density. The green particles are the star particles from the disc of the high-resolution model galaxy. Initially the stars are confined to the disc, but at $z=0$ they are spread along the orbital path of the galaxy which has an apocentre of 1000 kpc and a pericentre of 250 kpc. The virial radius of the cluster at $z=0$ is $\sim$2 Mpc.

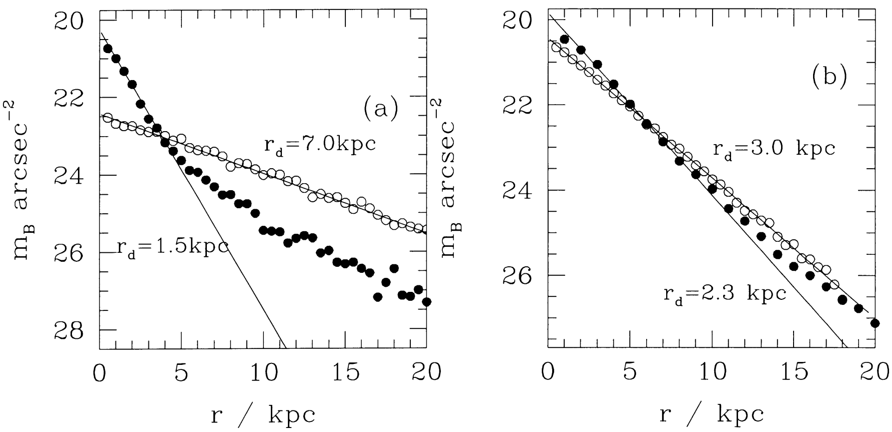

Figure 7. The open circles show the initial surface density of disc stars in (a) the LSB model galaxy and (b) the HSB model galaxy. The filled circles show the surface density at the final time after evolving within the cluster. The solid lines show exponential disc fits with the indicated scalelengths.

Table 1. Models to test disc stability as a function of potential depth and disc structure. Columns 2 and 3 are the disc scalelengths 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	r_h	M_{halo}/M_{disc} < 30 kpc	stars	dark matter
A	7 kpc	10 kpc	16	57%	92%
B	7 kpc	1 kpc	16	23%	40%
C	7 kpc	1 kpc	7	20%	35%
D	7 kpc	1 kpc	57	22%	41%
E	3 kpc	10 kpc	16	1%	93%
F	3 kpc	1 kpc	16	1%	35%
G	3 kpc	10 kpc	57	2%	60%

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 DISCS 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 disc, the disc scalelength, and the depth of the potential well provided by a dark halo. (A prominent stellar bulge will have an effect similar to that of a dark matter halo with a very small core radius.)

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

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

We know that a disc is highly unstable to mass loss, disruption and morphological transformation if both the halo core radius and disc scalelengths are large. Which parameter is more important? The answer is that neither is: they are both equally important. From Table 1 we can see that a galaxy with a scalelength of 3 kpc is stable against mass loss independent of the halo core radii, although their final disc scaleheights are significantly greater in the case of an extended halo. Furthermore, an extended disc that was highly unstable in a soft potential can be stabilized in a concentrated potential, although it suffers significant mass loss and large amounts of internal heating.

The core radius of the mass distribution makes a large difference to the extent of the final mass distribution. Models with $r_h = 10$ and 1 kpc (with the small disc) had final tidally limited radii of ~ 30 and ~ 50 kpc.

Models B, C and D are identical except for their disc mass, which varies by a factor of 8. The stellar and dark matter mass loss is very similar for all these models, and we cannot find any significant distinguishing feature between the final stellar systems. Although the discs lose over a fifth of their mass, the final objects are rotationally supported but suffer a lot of heating. Within a disc scalelength, 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 discs have large scaleheights (> 2 kpc) and they all look like extremely puffed-up low surface brightness S0 galaxies.

5 SUMMARY AND DISCUSSION

We have identified haloes 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 haloes with high-resolution model spiral galaxies with either LSB or HSB discs 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.

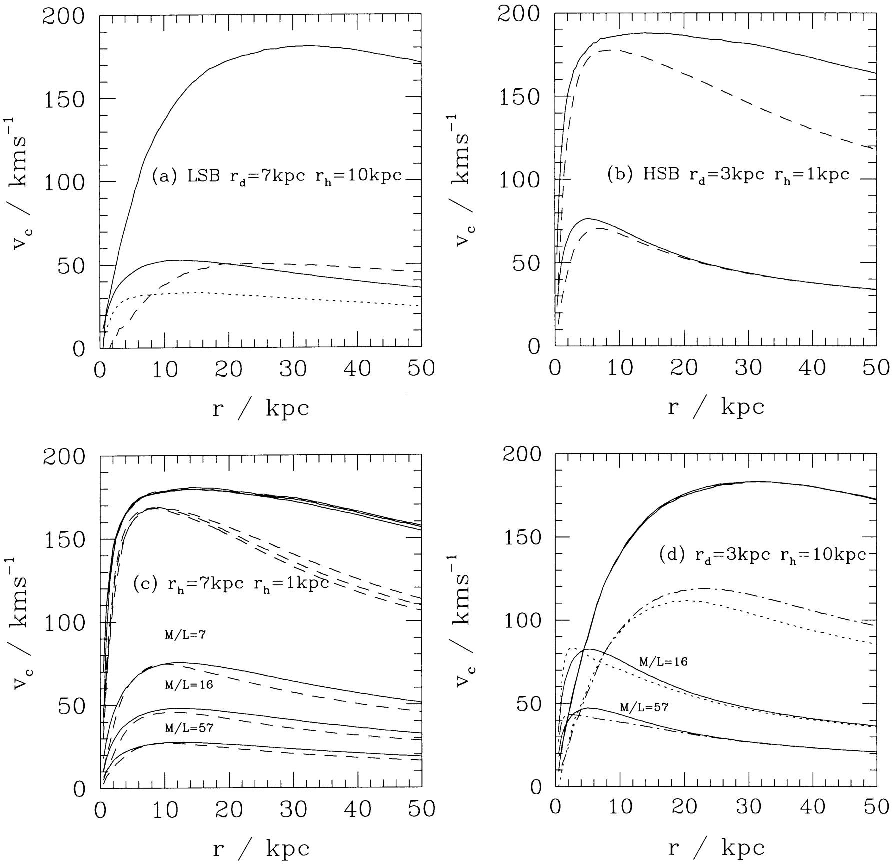

Figure 8. The contribution of the stars and dark matter to the rotational velocity of the seven test galaxies, all plotted in physical coordinates. The initial mass distributions are shown by the solid curves, whilst the final mass distributions are shown as dotted or dashed curves. The long-dashed and dotted curves in panel (a) show the halo and disc distributions respectively at the final time. The other galaxies in panels (b)–(d) lose much less mass, and it should be quite clear which component the broken curves respresent at the final time.

The response of a disc galaxy to tidal shocks is governed primarily by the concentration of the mass distribution that encompasses it and the disc scalelength. LSB galaxies have slowly rising rotation curves and large disc scalelengths, 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 intracluster light.

Recent observations of individual planetary nebulae within clusters, but outside of galaxies, lend support to this scenario. Estimates of the total diffuse light within clusters, using CCD photometry (Bernstein et al. 1995; Tyson & Fischer 1995) or the statistics of intracluster stars (Mendez et al. 1997; Theuns & Warren 1997; Feldmeier, Ciardullo & Jacoby 1998; Ferguson, Tanvir & von Hippel 1998), range from 10 to 45 per cent of the light attached to galaxies. Presumably these stars 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 haloes with high spin parameters (Dalcanton, Spergel & Summers 1997; Jiminez et al. 1998). Recent work by Lemson & Kauffmann (1999) demonstrates that the properties of dark matter haloes, including the 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 intracluster light within clusters may provide an upper limit to the maximum amount of light that can exist in LSB galaxies in the Universe.

HSB disc 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 disc scalelengths is short enough for the disc 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 discs and drive instabilities that can funnel gas into the central regions (Lake, Katz & Moore 1998; Gnedin 1999). A few Gyr after entering a cluster, their discs are thickened and no spiral features remain. If ram pressure is efficient at removing gas from discs, we speculate that these galaxies will evolve into S0s. Since the harassment process and ram-pressure stripping are both more effective near the cluster centres, we expect that a combination of these effects may drive the morphology–density relation within clusters.

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