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Evolutionary Processes in Clusters

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Abstract

Are the morphologies of galaxies imprinted during an early and rapid formation epoch, or are they due to environmental processes that subsequently transform galaxies between morphological classes? Recent numerical simulations demonstrate that the cluster environment can change the morphology of galaxies, even at a couple of cluster virial radii. The gravitational and hydrodynamical mechanisms that could perform such transformations were proposed in the 1970s, even before the key observational evidence for environmental dependences—the morphology-density relation and the Butcher-Oemler effect.

1.1 Introduction

Galaxies are observed to have a wide range of morphologies and stellar configurations, classified as disklike, with subclasses depending on the degree of disk instability, gas fraction, and central nucleation, or as spheroidal configurations of varying shapes and concentrations. Within both of these broad sequences we have various combinations of irregularities, subclasses, sizes, luminosities, and star formation histories. Observational studies of clusters and groups have played an important role in helping us to understand the origin of galactic morphologies. This is due to three main reasons: (1) evolutionary processes are accelerated in high-density environments, (2) some classes of galaxies are only found within larger virialized systems, and (3) clusters can be found easily at higher redshifts and therefore can be used to detect evolution directly.

The observational data are consistent with the idea that the visible baryons are concentrated at the center of much larger dark matter halos (Fischer et al. 2000). Thus, the interpretation of galaxy morphologies is closely linked to understanding dark matter clustering on different scales. The baryons are observed to have a scale length that is about 1/10th that of the dark matter, implying that dissipation must have played a key role in galaxy formation. On average, galactic mass halos have accumulated close to the universal baryon fraction, implying that violent feedback that leads to mass ejection of baryons has played a less important role in determining galaxy morphology. If most of the baryons quietly dissipated with little merging between subhalos, then the first galaxies to form are expected to be disks, due to conservation of angular momentum as the gas radiates energy, sinks within the dark matter halos, and spins faster. Indeed, most of the galaxies in quiescent environments (outside of other virialized systems) are disks—nearly all other classes of galaxies are found orbiting inside deeper potentials as satellite galaxies (halos within halos).

Spheroidal stellar configurations span a factor of 10^7 in luminosity, from central cluster cDs to the Local Group dwarf spheroidals, whereas the disks range from the giant low-surface brightness galaxies to the tiny Local Group dwarf irregulars. In general the spheroidals reach higher masses and luminosities. It is not obvious why this is the case. The gas cooling times cale limits the maximum size of cold baryonic systems, but it is a puzzle why we do not observe $\sim$30 kpc disks at the center of clusters where the cooling times are short. Perhaps harassment or local feedback from a central active galactic nucleus may be suppressing central disk formation in massive halos.

The fact that few spiral galaxies are found anywhere within the central regions ($\sim$Mpc) of rich clusters (Dressler 1980) could be explained in two ways: (1) cluster galaxies were never disks since they formed in a more merger-prone environment as lenticulars (S0), spheroidals (E), or dwarf ellipticals (dE); or (2) disks formed first and have subsequently been transformed into other morphological classes by virtue of the cluster environment that formed later. The *Hubble Space Telescope* allowed a direct observational test of the morphological change over the past few Gyr within dense and proto-dense environments. High-resolution images of the "Butcher-Oemler" (Butcher & Oemler 1978) clusters at $z \approx 0.5$ showed that the luminous spheroidal population was already in place at this epoch, but that the majority of the other galaxies were indeed disks (Dressler et al. 1997), and even the S0 population is deficient (Smail et al. 1997).

Many of these distant Butcher-Oemler clusters are complex merging systems of groups that will eventually have similar masses and galaxy densities to the nearby rich clusters like Coma. Clusters at high redshift that already have the mass and virial state of a rich cluster may already look similar to Coma (for example, MS 1054–03; van Dokkum et al. 1998). These comparisons are complex due to projection effects and background subtraction, but also the interpretation is difficult since frequently one is comparing systems identified at different epochs that are in different states of virialization.

1.2 The Paradigms for Disk and Spheroid Formation

In order for gas to concentrate and form stars at the centers of dark halos it must first be shock heated so that it can dissipate and cool to high densities. As it cools it must spin faster, as it conserves its primordial angular momentum generated from tidal torques (Hoyle 1951). The natural end state of cooling gas within an isolated dark matter halo is a rotationally supported disk; thus, one might postulate that disks are the initial building block from which the entire morphological sequence is constructed. Once the first disky objects have formed (or even while they are forming), a process of multiple mergers and the associated central gas inflows are expected to create the cD–E sequence that extends to the faintest ellipticals (the high-surface brightness, M32-like systems).

It should be remembered that this is primarily theoretical speculation—the details of this process are far from being worked out, and considerable numerical resources are required to fully investigate these ideas. Firstly, we need to understand how the gas is shock heated and cools to the central disk and how the angular momentum of the gas evolves during this process. Forming a bulgeless, late-type disk galaxy may be one of the most difficult challenges for the cold dark matter (CDM) model. Understanding the formation of spheroids has equally challenging problems. For example, why is there such a narrow spread in the luminosity of cD galaxies, and why do they lie offset brightward from the E galaxy luminosity function? Why are the smallest ellipticals rotating faster than the massive ellipticals?

Why are there so few isolated field ellipticals, which are the probable end state of the M_* groups, where M_* is the characteristic nonlinear mass today? The kinematics, colors, and ages of ellipticals are also challenges for this paradigm, which have yet to be understood. On a more general note, it is still unclear how CDM-type models that predict a steep mass spectrum of halos can produce a flat luminosity function, while at the same time matching the correlation between baryonic mass/luminosity and dynamical mass.

Independent of the model, we can pose the question of whether it is theoretically possible to reproduce the entire sequence of galaxies starting from disky systems. Starting with Holmberg's (1941) *N*-body experiments with lights and photometers, and later confirmed by Toomre's computer calculations (Toomre 1977), it has been shown that it is possible for galaxies to interact gravitationally and produce spectacular tidal features. Longer numerical calculations performed by Gerhard (1981) showed that the end states of mergers will violently relax into spheroidal configurations, but additional dissipation is required to produce the high phase space densities observed in ellipticals. As is usual with *N*-body simulations, the detailed comparisons can be quite complex, and the more details one simulates the more discrepancies one finds between data and theory (Naab, Burkert, & Hernquist 1999). More realistically, most ellipticals probably formed from the rapid and multiple mergers of a variety of baryonic systems—not too unlike a clumpy monolithic collapse—and distinguishing between the two standard hypotheses is difficult. However, in this review I will concentrate on "non-merging" mechanisms that can drive evolution and transform galaxies between and across morphological classes in the environments of galactic, group, and cluster halos.

1.3 Mechanisms for Transformation

Early theoretical work predicted that clusters of galaxies are harsh environments for galaxies to inhabit. Hydrodynamical processes (Spitzer & Bade 1951; Gunn & Gott 1972; Cowie & Songalia 1977; Norman & Silk 1979; Nulsen 1982) were proposed as important mechanisms for stripping the interstellar medium from galaxies. The importance of gravitational encounters and tidal forces as mechanisms for forming central cD galaxies, creating diffuse light, and for influencing morphological transformation was proposed by many authors in the 1970s and 1980s (Gallagher & Ostriker 1972; Ostriker & Tremaine 1975; Richstone 1976; White 1976; Hausman & Ostriker 1978; Merritt 1983).

Many of these mechanisms are efficient only in massive galaxy clusters, and they may be invoked to explain the morphology-density and Butcher-Oemler effects (Solanes & Salvador-Sole 1992; Kauffmann 1995). However, the role of evolution in lower-density environments may play an important role. The evolution of bright/massive galaxies within groups and poor clusters with velocity dispersions below 400 km s^{-1} should be dominated by dynamical friction and mergers. An important question remains: Is galaxy evolution in clusters driven by pre-processing of galaxies in groups? Indeed, star formation appears to be truncated within galaxies that lie in lower-density environments (Balogh, Navarro, & Morris 2000). However, it is clear that galaxies in virialized systems have different morphologies than the field. If environment is responsible for transition, then it should be possible to quantify observationally and theoretically where, when, and how these transitions take place.

In his excellent book on clusters, Sarazin (1988) makes six points to argue that the morphologies of galaxies are set at the time of formation rather than by subsequent environmental processes. Many of these points are still open questions. For example, Dressler (1980) claimed that the bulges of S0s are more luminous than those of the spirals, a frequently cited

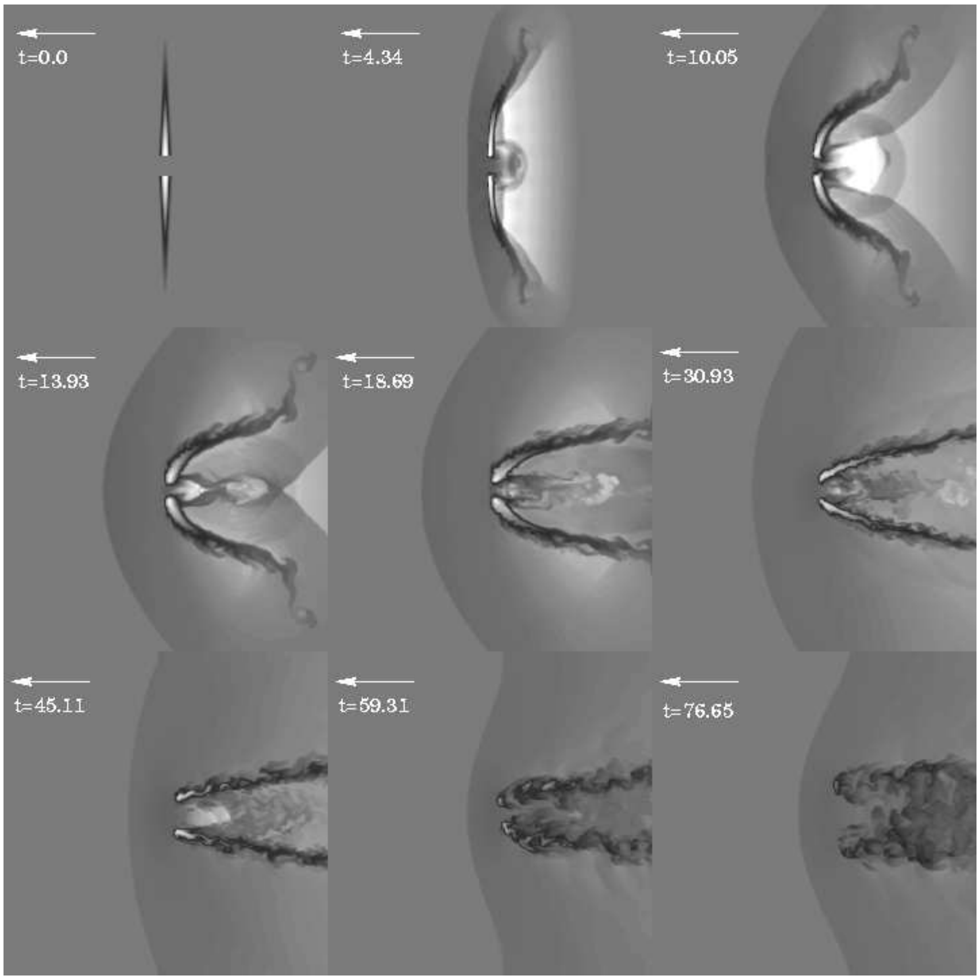

Fig. 1.1. A high-resolution Eulerian simulation of gas stripping of a galaxy falling into a gas density representative of the center of the Coma cluster at 3000 km s^{-1}. The time unit is millions of years, and each frame is 50 kpc on a side. (Adapted from Quilis et al. 2000.)

result that was disputed by Solanes, Salvador-Sole, & Sanroma (1989), who analyzed the entire Dressler sample and took into account additional selection effects. Most of Sarazin's arguments were made with the idea that gas processes would be driving a morphological evolution. Sarazin makes the point that gas dynamics would not reproduce the thick disks of S0s, although it is a natural outcome of gravitational interactions.

Indeed, recent numerical work has demonstrated that gravitational and hydrodynamical processes could be responsible for many of the observed aspects of galaxy morphology and evolution in different environments (Byrd & Valtonen 1990; Valluri & Jog 1991; Valluri 1993; Summers, Davis, & Evrard 1995; Moore et al. 1996b; Dubinski 1998; Moore, Lake, & Katz 1998; Abadi, Moore, & Bower 1999; Dubinski, Mihos, & Hernquist 1999; Mihos 1999; Balogh et al. 2000; Quilis, Moore, & Bower 2000; Vollmer et al. 2000; Mayer et al.

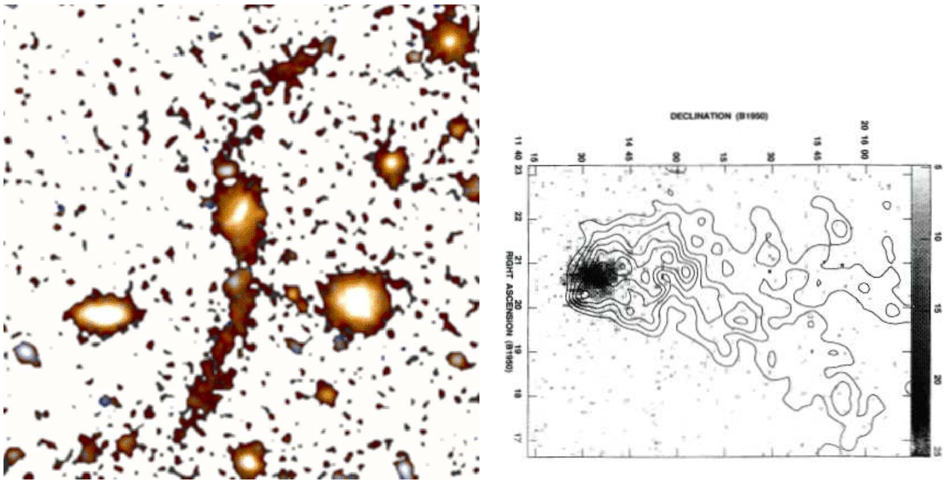

Fig. 1.2. The *left* image shows a symmetric stellar tidal tail from a disk galaxy that is orbiting in a galaxy cluster at $z = 0.5$ (courtesy of I. Smail and the MORPHS group). The *right* image shows the trailing radio emission from the hydrodynamical stripping of a cluster galaxy (courtesy of G. Gavazzi). Direct observational evidence for either gravitational or hydrodynamical effects is hard to find. In general, the tidal debris from harassed disks is too faint to observe, and ram pressure stripping acts on such a short time scale that it is rare to catch a galaxy in the act of being stripped.

2001; Vollmer, Balkowski, & Cayatte 2002; Gnedin 2003a,b). The following sections will discuss these studies in the context of understanding the wide variety of galactic morphologies.

1.4 A New Paradigm for the Formation of S0/dS0/dE/dSph/UCD Galaxies

Once a disky object has formed, then it may enter a denser environment, whether a galactic, group or cluster mass system. If the velocity dispersion of the deeper potential is more than $\sim$5 times the velocity dispersion of the infalling galaxy, then it is unlikely to merge with either the central object (by dynamical friction) or with another satellite. Only external processes will effect its evolution, and we can speculate, with support from numerical simulations, that the entire sequence of remaining galaxies (S0, dS0, dE, dSph...) is created by the transformation of spiral or dIrr systems by impulsive and resonant gravitational interactions, with some additional help from hydrodynamical processes.

Ram pressure stripping is effective at removing the entire gas supply from galaxies that pass through the cores of rich clusters (cf. Fig. 1.1). This will suppress star-formation in cluster galaxies, but will it be effective at large distances from the centers of clusters, where the gas density is low? Gravitational interactions may be important over a larger region of the cluster since more dark matter is bound to galaxies further from the central cluster potential (thus the encounters are stronger), but the number of encounters between halos decreases. The orbits of galaxies in clusters are nearly isotropic, which results in most of the galaxies orbiting through the dense inner region of the cluster (Ghigna et al. 1998). In fact, 10% of orbits will take galaxies through the core and to beyond twice the cluster virial radii ($\sim$6 Mpc for Coma). Therefore, the environment near rich clusters may host galaxies

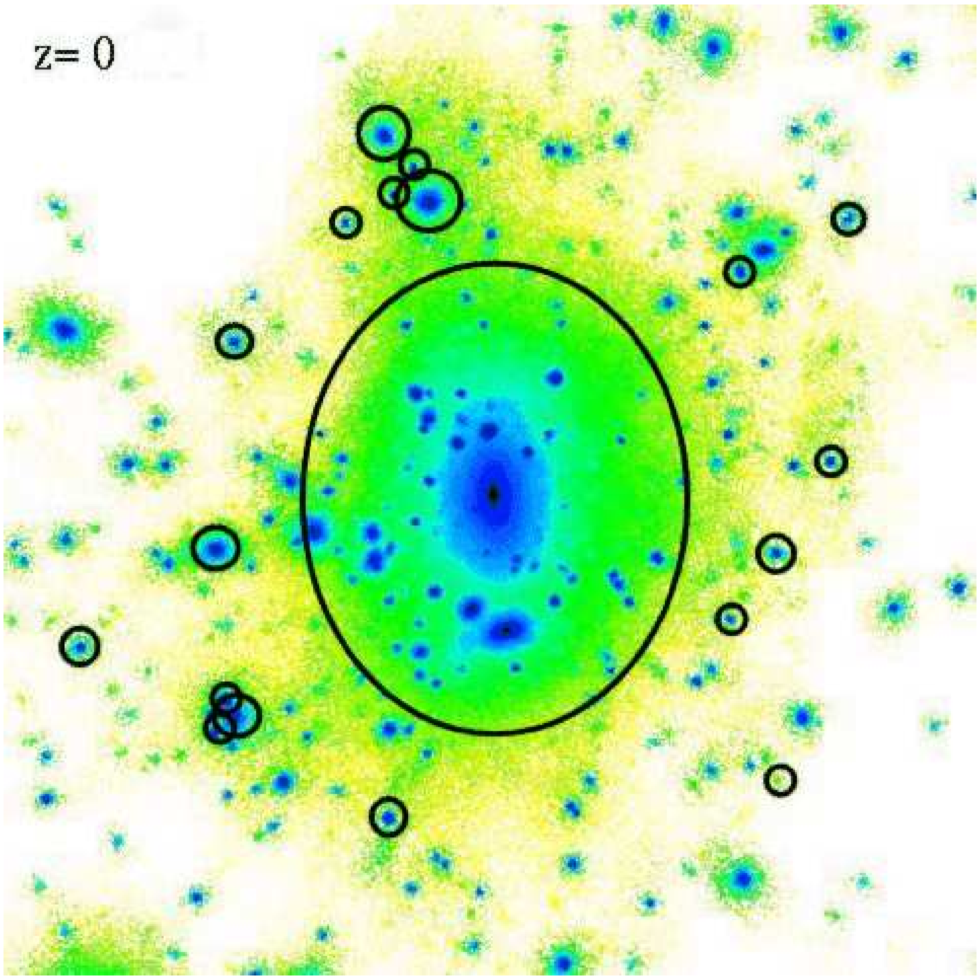

Fig. 1.3. The density of dark matter plotted to 3 virial radii for a high-resolution simulation of a galaxy cluster. The large inner circle is the virial radius of the cluster. The smaller circles highlight halos that are currently outside the cluster but have orbited within $0.25\,r_{200}$. (This is the final frame of the mpeg movie showing the formation history of this cluster and can be downloaded from www.nbody.net.)

that have suffered significant gravitational perturbations and have been partially stripped of gas (cf. Figs. 1.2 and 1.3) by virtue of orbiting through the cluster core.

The definition of an S0 is basically a featureless disky galaxy with little or no interstellar medium, so the simplest way to create an S0 is to remove the interstellar medium from a Sa/Sb disk (Solanes et al. 1989; Solanes & Salvador-Sole 1992). We have two possible methods for accomplishing this. Any galaxy passing through the core of a massive cluster will have its gas supply completely stripped by ram pressure and viscous stripping on a time scale shorter than the core-crossing time. The remaining dense molecular gas may recycle into the interstellar medium and also be removed or consumed in a burst of star formation due to the pressure increase as the galaxy reaches the cluster center. Alternatively, gravitational interactions with the cluster and its substructures will heat disks, raising the Toomre "Q" parameter, which naturally suppresses spiral structure and other instabilities in the disk, further suppressing star-formation as molecular cloud growth is halted (Moore et al. 1998; Gnedin 2003a,b).

1.4.1 Cluster Dwarf Ellipticals (dEs) and Transition Galaxies (dS0s).

Dwarf ellipticals are the most numerous type of galaxy in clusters (Binggeli, Sandage, & Tammann 1985). They are flattened exponential systems, sometimes with a bright, compact nucleus. These systems are in various dynamical states, ranging from pressure-supported spheroids to rotationally flattened disky systems (Geha, Guhathakurta, & van der Marel 2002). Numerical simulations of disks orbiting within cluster potentials have shown that a dramatic transformation to a diffuse spheroidal system is likely to occur (Moore et al. 1996b). The transformation sequence begins with a violent bar instability. Subsequent perturbations cause the bar to lose angular momentum, and it eventually collapses into a spheroidal system through a buckling-type instability. During the early stages of the transformation, which takes roughly a cluster orbital time, the morphology of the galaxy may appear as a rotationally supported dS0 system.

A fundamental prediction from gravitational heating mechanisms is that dEs should be embedded within very low-surface brightness tidal streams of stellar debris, as demonstrated in Figure 1.4, and these streams should trace the orbital path of the progenitor galaxy. Since the relaxation time is only short in the cluster cores, these streams should survive relatively intact at the edge of clusters, but they should become well mixed near the cluster centers.

1.4.2 Intracluster Diffuse Light, Overmerging, and UCDs

The nature of the dark matter is critical to the survival of galaxies in clusters. If galaxies had constant-density cores of just a few kpc (or cuspy potentials with very low concentrations), then they would all be easily disrupted by the cluster potential. This process is directly analogous with the overmerging problem that was responsible for the dissolution of subhalos in early *N*-body simulations (Moore, Katz, & Lake 1996a). On the other hand, if galactic halos are cuspy and concentrated they would all survive in clusters and we would not expect to observe a significant component of diffuse light.

The "ultra-compact dwarfs" (UCDs) recently found in the Fornax cluster are most likely the dense nuclei of nucleated dE galaxies that have been "overmerged" by gravitational interactions (Drinkwater et al. 2000). These tracer cores show that the central concentrations of the progenitor galaxies must have been low enough so that they have been completely disrupted by the present day. Both the fraction of diffuse light stripped from galaxies and the abundance and locations of the UCDs could be used to constrain the structure of galaxies and the efficiency of gravitational interactions in different environments.

1.4.3 Local Group Dwarf Spheroidals

The Local Group dwarf spheroidals are the extreme tip of the galaxy luminosity function, and, as the shallowest potentials and faintest galaxies known, they provide a strong test of our understanding of galaxy formation (Kormendy 1989). The Local Group morphology-density relation is similar to that of rich clusters in that the spheroidal galaxies with no diffuse gas are located close to the host galactic potentials of the Milky Way and

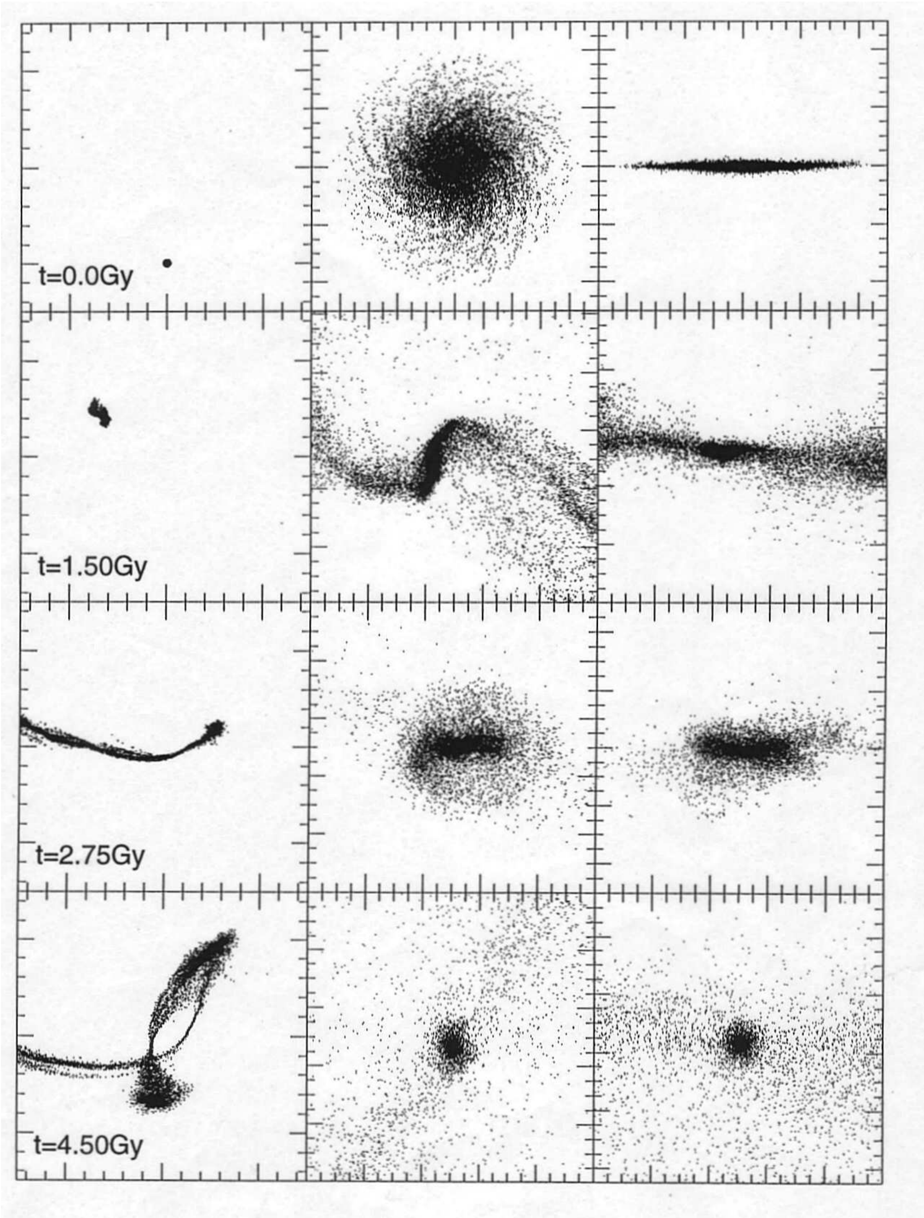

Fig. 1.4. Gravitational tides from a deeper potential are sufficient to drive an evolution from disks to dwarf spheroidals. Here I show the evolution of an Sc spiral galaxy on a 6:1 (apo:peri) orbit, where the pericenter is $0.1\,r_{virial}$ and the ratio of circular velocities of the two systems are 5:1. This system could therefore be rescaled to represent a galaxy like the SMC orbiting within the Milky Way or an L_* low-surface brightness galaxy orbiting in a galaxy cluster. The left frame shows the entire orbit, while the center and right frames are face-on and edge-on views centered on the galaxy. The forced bar instability is so violent that the evolution is better described by a secondary violent relaxation of the stellar disk—most of the galaxy is stripped into symmetric debris streams leaving a small pressure-supported spheroidal galaxy with an exponential light profile (courtesy of C. Calcaneo-Roldan).

M31. Again, we can ask the question: Do disks know not to form near the site of a massive potential, or were they originally disks that have been transformed to spheroidals through interactions? Observationally this is unclear and a difficult question to answer because we cannot observe Local Group progenitors at high redshifts.

However, a huge amount of detailed data exists for these faint Local Group galaxies (e.g., Grebel 2001), which must be reproduced by a successful model for their formation. Simulations of galaxy formation in a cosmological context that can resolve the faintest satellites are some years away; therefore, only the most basic comparisons between theoretical models and data have been made to date. The dynamics of these systems indicate that their spheroidal shapes are due to random stellar motions and that rotational support is small. Many of these systems show evidence for continuous star formation or widely separated bursts, indicating that ram pressure stripping by a hot Galactic halo component has not been completely efficient at removing their fuel. It also indicates that supernovae winds have not been effective at ejecting the bulk of the gas from these systems.

Galaxies are on average some 5 Gyr older than galaxy clusters, which allows time for gravitational interactions to transform disks to dSphs in the potential of a more massive system (Mayer et al. 2001). A high-density, Draco-like dSph must have had a progenitor with a similar high dark matter density, such as the dIrr galaxy GR8. However, one should not compare GR8 directly with Draco since GR8 has evolved for 10 Gyr longer in the field than the system that accreted into the Galaxy to evolve into Draco. The morphological transformation predicted by the numerical simulations is similar to that for cluster galaxies, but on a longer time scale since only the main galactic potential has been considered as the perturber. If the CDM model is in fact correct, then the transformation for the dSphs may be more rapid due to encounters with dark matter substructure predicted to fill galactic halos.

1.5 Conclusions

Numerical simulations have shown that environmental processes are sufficient to reproduce some of the basic properties of a large fraction of the Hubble sequence (S0, dE, dS0, dSph, UCD) by gravitationally interactions acting on disks. Hydrodynamical processes can can also play a role in suppressing star formation on a shorter time scale, but only in regions of high gas density. Dramatic improvements to the modeling will come when algorithms have improved to the extent that we can form realistic disk systems from *ab initio* initial conditions. This will allow the morphological evolution in groups and clusters to be studied in great detail and within a cosmological context, enabling quantitative observational comparisons and predictions to be made. Realistically, this is probably 5–10 years away. For comparison with theory, observers need to quantify the Butcher-Oemler effect using mass-selected samples of clusters at different epochs through a combination of lensing and high-resolution spectrophotometric data. Probing down to dwarf galaxy luminosities and group mass scales will be of great interest to theorists working to constrain evolutionary scenarios and cosmological models.

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