Dynamical effects on galaxies in clusters

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Abstract. The observed morphological evolution since $z \sim 0.5$ within galaxy clusters provides evidence for a hierarchical universe. This evolution is driven by dynamical effects that operate within the cluster environment – suppression of star-formation by ram-pressure and viscous stripping of the intra-galactic medium and tidal heating of disks by gravitational encounters.

1. Evidence for a hierarchical universe?

A hierarchical universe with a low matter density is the currently favoured model for structure formation. However, observational evidence for evolution is scarce - structures appear old and similar over moderate look back times (Peebles 1999). Galaxy clusters are the most massive virialised objects in the universe and are the latest systems to form, therefore they may reveal evidence for recent evolution. Indeed, perhaps the strongest indication for evolution can be found by examining galaxy morphologies in rich clusters over the past 5 Gyrs (i.e. references within: Sandage et al. 1970 Butcher & Oemler 1978, Dressler 1980, Dressler & Gunn 1983, Couch et al. 1987, Binggeli et al. 1988, Ferguson & Sandage 1991, Binggeli et al. 1991, Thompson & Gregory 1993, Peterson & Caldwell 1993, Lavery & Henry 1994, Barger et al. 1996, Dressler et al. 1997, Balogh et al. 1998, Couch et al. 1998, Poggianti et al. 1999, Bower et al. 1999). At $z \sim 0.5$ we see that clusters of galaxies contain predominantly late type disk galaxies that have undergone a transformation into dwarf ellipticals (dSph) by the present day. There is also compelling evidence that the fraction of S0 galaxies decreases over the same look back time (Dressler et al. 1997), whilst at even earlier epochs, tentative evidence for the hierarchical growth of the cluster elliptical galaxies may be found (van Dokkum et al. 1999).

The data suggest that the cluster environment is causing a morphological transformation between galaxy types. Other indicators of environmental influences in clusters include the morphology-density relation (Dressler 1980), signatures of star-bursts followed by a rapid truncation of star-formation in cluster spirals and k+a/a+k galaxies (Poggianti et al. 1999), the absence of low surface brightness disks in clusters (Bothun et al. 1993) and the presence of a large component of diffuse star-light (Bernstein et al. 1993, Freeman - this volume). In this paper we will discuss the role of environment and the proposed mechanisms that are responsible for driving galactic evolution in clusters and creating the “morphological and spectroscopic Butcher-Oemler effects”. 
2. Mergers, Winds, Harassment & Stripping

Several mechanisms have been proposed that can induce a morphological transformation between galaxy classes. Toomre & Toomre’s (1972) pioneering n-body simulations of merging spirals gave rise to elliptical remnants. This process is most effective when the encounter velocity is comparable to the galaxies internal velocity, therefore mergers should be rare within rich virialised systems, a fact pointed out by many authors (e.g. Mamon - this volume), however see van Dokkum (1999). Numerical simulations of clusters that formed naturally in a hierarchical universe show that mergers are indeed rare (Ghigna et al. 1998). Galactic winds from supernovae are frequently cited as important mechanisms for dwarf galaxy evolution (Dekel & Silk 1986) yet observational evidence for this process is not compelling (Martin 1998) and it is unlikely that feedback can reshape the stellar configuration.

We therefore focus on the two mechanisms that are most likely to operate extensively in the cluster environment (c.f. Fujita 1999). Impulsive heating via rapid tidal encounters has been demonstrated to be an efficient mechanism at heating disk galaxies in clusters – termed “galaxy harassment” by Moore et al. (1996, 1998), tidal forces and internal cluster dynamics have been studied by many authors, including Richstone & Malmuth 1983, Icke 1985, Merritt 1985, Byrd & Valtonen 1990, Valluri & Jog 1991, Valluri 1993, Gnedin (1999). Gunn & Gott (1978) suggested that the ram-pressure force of the hot intra-cluster medium could remove the atomic hydrogen from disks falling into clusters. Nulsen (1982) proposed that the viscous and turbulent stripping of gas would be equally as effective.

Morphological transformation by gravitational encounters is a process that requires several strong or frequent tidal collisions and acts over a timescale of several $\times 10^9$ years. In contrast, hydrodynamic effects operate on a much shorter timescale, $\sim 10^7$ years. Observational evidence for gas-dynamical interactions in clusters is scarce due to the speed at which the process occurs (Stevens et al. 1999), however the literature does contain some examples (i.e. Warmels 1988, Cayatte et al. 1990, Gavazzi et al. 1995, Kenny & Koopman 1999, and several recent studies in this volume by Vollmer et al. (1999), Ryder et al. (1997) & J. Solanes et al.).

The first 3-dimensional calculation of ram pressure stripping using realistic disk galaxy models was carried out by Abadi et al. (1999). Earlier work had studied the properties of spherical systems in two dimensions (i.e. Balsara et al. 1994). Abadi et al. found that the simple analytic argument proposed by Gunn & Gott (1972) balancing the ram pressure, $\rho_{ICM}v^2$, with the disk’s gravitational restoring force works very well. Simulations at $45^\circ$ and edge on to the motion through the intra-cluster medium suffered slightly less stripping than face on. However, even in the best case scenario for stripping, an $L_*$ disk galaxy moving through the center of the Coma cluster at 3000 km s$^{-1}$, a significant fraction of gas remained (HI extending to a radius $\sim 5$ kpc) that would continue to form stars.
A more realistic treatment of the stripping process using a Eulerian finite difference code revealed that the turbulent and viscous stripping processes help to remove more gas than just the ram pressure alone (Quilis et al. 1999). Quilis et al. also realised that disks are not smooth homogeneous mediums, but have a complex structure containing many holes and regions that are completely devoid of gas (Brinks & Bajaja 1986). Once these are included, the ICM streams through the holes, preventing “backside infall” and ablates away the gas from their edges, rapidly removing the entire HI content of disks. Thus, these authors find that the stripping process alone, is in general 100% efficient at removing the HI component within a timescale $\lesssim 10^7$ years (see Figure 1).

Without fresh material to replenish GMC’s, star formation will be rapidly truncated (Elmegreen & Efremov 1997). Continued heating by tidal encounters with massive galaxies increases the disk scale height by factors of 2–3. Spiral features will be suppressed and these galaxies will resemble the S0 galaxies observed in nearby clusters. The efficiency of the stripping process increases

Figure 1  The time evolution of the diffuse HI component within a spiral galaxy falling into the Coma cluster (Quilis et al. 1999).
rapidly towards the cluster center where $\rho_{ICM}$ and $v$ are maximum, thus we have a natural way of creating the morphology-density relation. Whether or not the transformation of Sa/Sb galaxies to S0’s can reproduce the same scaling as observed remains to be tested.

Galaxy harassment will transform dI/Sc/Sd disks into dwarf elliptical (dSph) galaxies over a timescale of several billion years - i.e. several cluster orbital periods. Simulations of this process appear to produce remnant galaxies that closely match the observed cluster dwarf’s (Moore et al. 1996, 1998), although the sample of kinematical data is small. A fundamental prediction of the formation of dE (dSph) galaxies by tidal heating is that the remnant galaxies are embedded in diffuse streams of stars, tidally removed from the progenitor disks (see Figure 2). The surface brightness profiles of these galaxies are expected to be well fitted by an exponential profile over their central regions but a significant excess of stars will be found at 4–5 scale lengths (Moore et al. 1999). The surface brightness of this excess will occur fainter than $27 - 28M_B$ per arcsec$^{-2}$, an observable effect with 4m or 8m class telescopes. The presence of freely orbiting planetary nebulae in clusters (Freeman, this meeting) provides strong support for the efficiency of this process.

Not surprisingly, low surface brightness disks are not found within clusters (Bothun et al. 1993). The shear extent of their stellar distributions and low central potentials make them unstable to tidal forces. Once these galaxies enter the cluster environment, most of there stars are tidally removed and a diffuse spheroidal remnant remains (Moore et al. 1999). Numerical simulations of this process can be used to study the diffuse cluster light component.

**Figure 2** An example of tidal tails from the galaxy harassment process from the cluster CL0054-27 at z=0.56 courtesy of Ian Smail. The image is roughly 150 kpc on a side. Features this prominent are rare at this surface brightness ($\sim 27M_B$ per arcsec$^{-2}$) but are expected to surround all cluster dE (dSph) galaxies at lower surface brightness levels.
3. Conclusions

Two mechanisms are necessary to reproduce the observed morphological evolution of galaxies in clusters. At the faint end of the luminosity function, disk galaxies are easily transformed into dE (dSph) galaxies by galaxy harassment. Numerical simulations of this process predict that all dwarf galaxies in nearby clusters will be embedded within very diffuse streams of stripped stars. Low surface brightness disks with slowly rising rotation curves and shallow central potentials will not survive the fluctuating potentials of rich clusters and will be tidally shredded to form the bulk of the diffuse intra-cluster light. Spirals with bulges are more stable to gravitational encounters. They would retain their stars and gas and continue to form stars to the present day. Most, if not all of the atomic hydrogen of these galaxies must be rapidly removed upon entering the cluster environment in order to explain their star-formation histories. Fluid dynamic simulations of realistic disks moving through a hot ICM demonstrates that a combination of ram-pressure and viscous stripping can remove 100% of the HI from the IGM within $10^7$ years. Continued tidal heating by encounters will complete a transformation to the S0 class.

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