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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 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 1970's, even before the key observational evidence for environmental dependences - the morphology-density relation and Butcher-Oemler effects.

1.1 Introduction

Stars are arranged into a variety of configurations that are broadly called disks with subclasses depending on the degree of disk instability, gas fraction and central nucleation, or ellipticals of varying shapes and concentrations. Amongst both of these sequences we have various combinations, irregularities, subclasses, sizes, luminosities and star formation histories. Observational studies of clusters and groups has played an important role in helping to understand the origin of this morphological sequence. This is due to three main reasons: evolutionary processes are accelerated in high density environments, some classes of galaxies are only found within larger virialised systems and 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 etal 2000). Thus the interpretation of galaxy morphologies is closely linked to understanding dark matter clustering on different scales. On average, galactic mass halos have accumulated close to the universal baryon fraction (Mayer & Moore 2003), and typically the baryons have a scale length that is about 1/10th of that of the dark matter. This implies that dissipation must have played a key role in galaxy formation and that violent feedback and mass ejection a less important role. If most of the baryons quitely dissipated with little merging between subhalos, then the first galaxies to form are expected to be disks due to conservation of angular momentum. Indeed, most of the galaxies in quiet environments (outside of other virialised 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 cD's to the local group dwarf spheroidals - whereas the disks range from the giant LSB's to the tiny Local Group dIrr's. In general the spheroidals reach higher masses and luminosities. It is not obvious why this is the case - cooling timescales are not the entire answer since we observe little evidence for ∼20kpc disks at the centre of clusters where the cooling times are short. Perhaps harassment or local feedback from a central AGN may be suppressing central disk formation in massive halos.

The fact that few spiral galaxies are found anywhere within the central regions (∼Mpc) of rich clusters (Dressler 1980) could be explained in two ways: (i) cluster galaxies were never disks since they formed in a more merger prone environment as lenticulars (S0), spheroidals (E) or dwarf ellipticals (dE), or (ii) 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 Gyrs within dense and proto-dense environments. High resolution images of the "Butcher-Oemler" (Butcher and Oemler 1978) clusters at $z \sim 0.5$ showed that the luminous spheroidal population were already in place at this epoch but that the majority of the other galaxies were indeed disks (Dressler etal 1997), and even the S0 population is difficient (Smail etal 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 e.g. MS1054 (van Dokkum etal 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 virialisation.

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 is primordial angular momentum generated from tidal torques (Hoyle 1949). The naturally end state of cooling gas within an isolated DM 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 whilst they are forming) then 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. For example, why is their such a narrow spread in the luminosity of cD galaxies and how can we reproduce their offset from the galaxy luminosity function? Why are the smallest ellipticals rotating faster than the massive ellipticals? Why are there so few isolated field ellipticals that are the probable end state of the M_* groups, where M_* is the characteristic non-linear mass today? The kinematics, colours and ages of ellipticals are also challenges for this paradigm that have yet to be understood.

Even the principles behind the formation of disks is a long way from being validated – most importantly 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. However, at least there is a paradigm to test but it is clear that one of the most difficult challanges for the

CDM model is to make a pure bulgeless disk galaxy. Independent of the model, we can pose the question whether it is theoretically possible to reproduce the entire sequence of galaxies starting from disky systems?

Starting with Holmberg's N-body experiments with lights and photometers and later confirmed by Toomre's computer calculations, it is possible for galaxies to interact gravitationally and produce spectacular tidal features. Full merger calculations performed by Gerhard (1981) showed that the end state of mergers will violently relax into elliptical 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 descrepancies one finds between data and theory (Naab etal 1999). More realistically, most ellipticals probably formed from the rapid and multilpe 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.

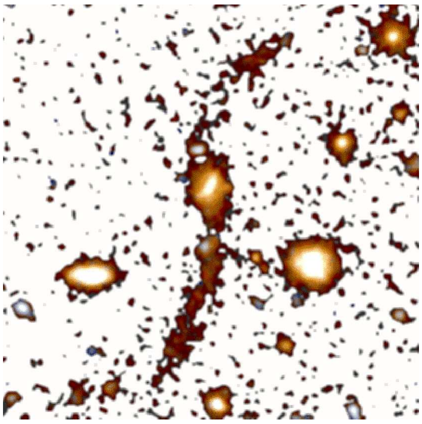
1.3 Mechanisms for transformation

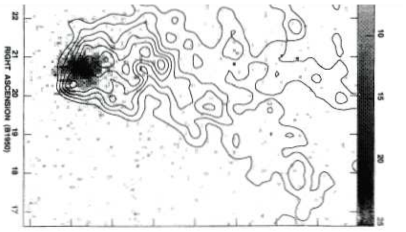
Early theoretical work predicted that clusters of galaxies are harsh environments for galaxies to exist. Hydrodynamical processes (Spitzer & Bade 1950, Gunn & Gott 1972, Cowie & Songalia (1977), Norman & Silk (1979), Nulsen (1980) were proposed as important mechanisms for stripping the interstellar medium from galaxies. The importance of gravitational encounters and tidal forces as a mechanism for forming central cD galaxies, creating diffuse light and for influencing morphological transformation was proposed by many authors in the 1980's (Gallagher & Ostriker 1972, Ostriker & Tremaine 1975, Richstone 1976, White 1976, Hausman & Ostriker 1977, Merritt 1983).

Within clusters we have mechanisms that could explain the morphology density and Butcher-Oemler effects (Solanes etal 1992, Kauffman 1995). The evolution of bright/massive galaxies within groups and poor clusters with dispersions below 400km/s must be dominated by dynamical friction and mergers. An important question remains - is galaxy evolution in clusters driven by pre-processing of galaxies in groups? One must also explain the truncation of star-formation in galaxies at overdensities that correspond to groups and lower local density environments (Balogh etal 2000). Clearly galaxies in virialised systems have different morphologies than the field. If environment is responsible for transition, then it is important to quantify observationally and theoretically where, when and how these transitions take place.

In his excellent book on clusters, Sarazin (1980) 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 S0's are more luminous than those of the spirals – a frequently cited claim that was disputed by Solanes etal (1989) who analysed the entire Dressler sample and took into account some of the selection effects. Most of Sarazin's points are taken 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 S0's, but it is a natural outcome of gravitational interactions.

Indeed, recent numerical work has demonstrated that gravitational and hydrodynamical

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