PROCEEDINGS OF SCIENCE

Environmentally-Driven Galaxy Evolution

Stephanie Tonnesen[*]
Princeton University
E-mail: `stonnes@astro.princeton.edu`

The galaxy population in clusters differs from that in the field. The cluster galaxy population (at $z \leq 0.4$) is dominated by red, early-type galaxies. Although some of this can be explained by the mass-morphology relation, in this proceedings I discuss work that has shown that, particularly in low-mass galaxies, there is environmentally-driven evolution from blue (star-forming) to red (non-star-forming). While environment can be measured in several ways, I show that local environment affects galaxies up to the scale of the halo in which they reside. Focusing on clusters, I introduce the different mechanisms that can affect galaxies: galaxy-cluster, galaxy-galaxy, and galaxy-intracluster medium interactions. I then give an overview of the evidence that the color-evolution of galaxies from blue to red is reflected in the morphological evolution of galaxies from spiral to S0, and discuss the necessary steps in the evolution of spirals into S0s. I then briefly describe some of my own research examining the role of ram pressure stripping on the morphological evolution of spiral galaxies. While ram pressure stripping can effectively remove the fuel for star formation and redden galaxies, this will form S0s that are less luminous than their spiral progenitors. Therefore, while ram pressure stripping may be an important mechanism driving the formation of S0s from spirals, it cannot be the only process driving this morphological evolution.

Frank N. Bash Symposium 2011: New Horizons in Astronomy
October 9-11, 2011
Austin, Texas, USA

PoS(Bash11)008

---

[*] Speaker.

1. Introduction

In our hierarchical view of the universe, smaller halos are formed before larger ones, and large halos grow by accretion of satellites. Galaxies form, then come together to form groups and clusters. Does entering into these dense environments affect galaxy properties?

To answer this question, it is important to examine the variety of galaxies seen in our universe. The first step in this process is to categorize galaxies in ways that give us insight into their fundamental properties, and in this proceedings I will first highlight some of the methods by which galaxies have been classified (Section 2). I will then discuss whether and how galaxies evolve due to their environment (Section 3), and in Section 3.1 I will discuss the different ways in which environment can be defined. Focusing specifically on clusters (Section 4), I will introduce mechanisms that can drive the evolution of galaxies (Sections 4.1 and 4.2). Finally I will discuss the morphological evolution of spiral galaxies into S0s (Section 5), and work I have done to understand the role of ram pressure stripping in driving this evolution. I will conclude by summarizing my main points and mentioning a few avenues for future work.

2. Galaxy Types

The Hubble Sequence uses galaxy morphology to categorize galaxies [43]. Elliptical galaxies are those with ellipsoidal shapes, and spiral galaxies have flatter shapes and thus look more like disks. They also have spiral structure in their gas and stellar distribution. S0s have large bulges, like elliptical galaxies (which can be considered all bulge), and featureless disks.

It has been found that the color of galaxies is related to their Hubble type [25, 26, 80]. Elliptical galaxies tend to be redder in optical color than spiral galaxies (but see [15] for a discussion of red disk-galaxies). The bluer color of spiral galaxies is due to the younger stellar population in spirals. Galaxy color is an indicator of star formation history, or the age of the stellar population (although color is also affected by metallicity and dust, which can confuse this relation).

In addition, the most luminous galaxies tend to be red early-type galaxies (ellipticals) [12, 3]. Baldry et al. [3] find, using more than 65,000 galaxies from the Sloan Digital Sky Survey, that brighter than $M_r \sim -22$, more than 60% of galaxies are from the authors' red distribution of galaxies (and at $M_r \sim -23.5$ nearly the entire population is red).

The relationship between galaxy color (or star formation history) and luminosity (or mass) can be physically explained in a cold dark matter universe by how galaxies of different masses accrete gas. In early models of galaxy formation through spherical collapse, gas falling into a dark-matter halo is shock-heated to the virial temperature. This gas then slowly cools and falls towards the center of the halo to form the dense central luminous galaxy [70, 75, 9, 90, 30]. This leads to an upper mass threshold at which shocked gas can no longer cool within a Hubble time, and these high mass galaxies will therefore have no fuel for star formation. In lower mass halos gas does not go through an accretion shock at the virial radius, and will either never become hot or will be able to cool quickly [70, 90].

Recent numerical cosmological simulations have verified that not all gas is shock-heated to the virial temperature of the halo (e.g. [48]). Some gas penetrates the halo as unshocked cold flows, and the fraction of shock-heated gas depends on the halo mass [48, 47, 63, 13] . Kereš et

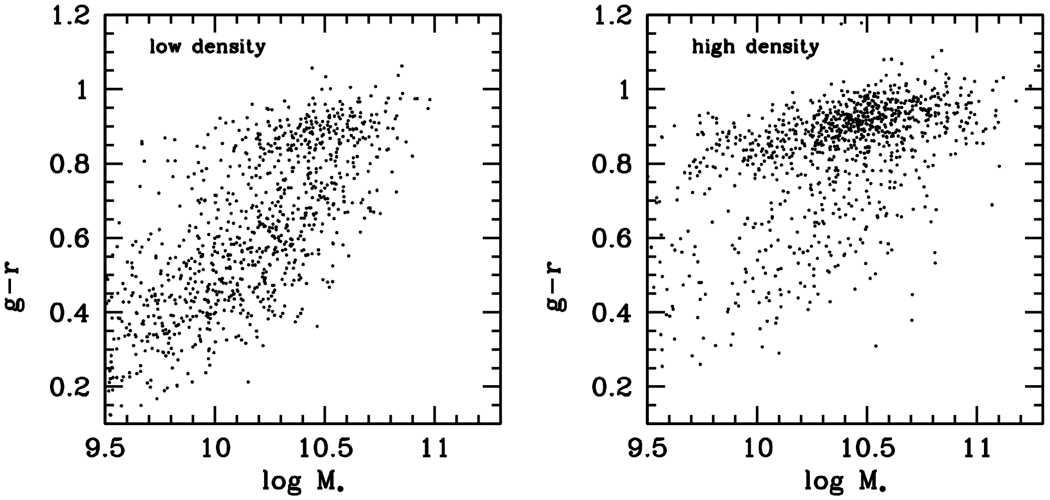

Figure 1: Figure 6 from Kauffmann et al. [46]. A plot of $g-r$ color versus stellar mass for the 1000 galaxies in the lowest density bin on the left and in the highest density bin on the right. Note the extension of the red sequence to lower mass galaxies in the right panel.

al. [48] find that cold accretion dominates in low redshift halos that have a total mass below $\sim$5 $\times$ 10^{11} $M_\odot$. If cold gas accretion is equated with the ability of a galaxy to form stars, then this indicates that higher mass galaxies should be redder than low mass galaxies. As discussed above, this is indeed observed in the galaxy color-magnitude diagram [12, 3]. However, as is clear from Figure 5 in Kereš et al. [48], there is still significant scatter in the fraction of gas accreted at low temperatures at a single galaxy mass. A range of galaxy colors is also seen at a single galaxy mass when examining the color-magnitude diagram (e.g. [3]).

Therefore, it is clear that while mass has an important influence on whether a galaxy can accrete cold gas and form stars, it is not the only factor to consider when understanding galaxy color (and other characteristics). While galaxy properties may be influenced by merger and mass accretion history, feedback from stellar winds, supernovae, and black holes, I will focus on the environment.

3. Galaxies and Environment

In addition to being the first to categorize galaxies, Hubble also found that galaxy morphology is correlated with environment [44]. The galaxy population in nearby clusters is dominated by red early-type galaxies, while galaxies in the field tend to be of later types [44]. The relationship between morphology and local galaxy density was quantified as the morphology-density relation [28, 64]. Galaxy color is also related to local galaxy density. Galaxy morphological type and star formation rate (SFR) has been found to smoothly change to later types with higher SFRs with increasing clustercentric distance [79, 87].

The morphology- and color-density relations can depend on galaxy mass. The stellar masses of galaxies tend to be larger in clusters [5, 12], so the relationship between galaxy mass and environmental density (and galaxy mass and color, as discussed in Section 2) can somewhat account for the color-density and morphology-density relations. However, Kauffmann et al. [46] find that star formation history depends on local galaxy density for all galaxies regardless of mass, and that in galaxies with stellar masses less than 10^{10} $M_{\odot}$ there is a relationship between galaxy morphology and local density. Further, in their Figure 6 (shown in Figure 1), the authors show color-mass diagrams for galaxies in their lowest- and highest-density regions. The red sequence for galaxies in high-density regions extends to lower galaxy masses than that for galaxies in low-density regions, indicating the importance of environment in reddening at least low-mass galaxies. Indeed, Kereš et al. [48] cite environment as an explanation for their low-mass galaxies with no cold gas accretion.

These correlations alone do not indicate whether environment affects the formation or subsequent evolution of galaxies. However, the Butcher-Oemler effect, that galaxies in clusters beyond z$\sim$0.4 tend to be bluer than galaxies in nearby clusters, is empirical evidence that spirals evolve over time after they enter the cluster environment [17]. In addition, the spiral to S0 ratio decreases with redshift [29, 31, 27]. Both the morphology-density and color-density relations have been observed at a redshift of 1, but the fractions of early-type and red galaxies continue to increase with decreasing redshift [76, 66].

3.1 Defining Galaxy Environment

When examining galaxy color or morphology relative to environment, a number of different environmental definitions can be used. Comparisons can be made between galaxies that are cluster members and those that are in the field [37, 64, 17]. Clustercentric distance can also be used as an environmental measure [52, 28, 91, 87, 77]. Local galaxy density is also frequently used as an environmental measure. This is often measured in one of two ways: 1) measuring the projected local galaxy density using the distance to the n^{th} nearest neighbor (e.g. Dressler [28]; Gomez et al. [34] used the tenth nearest neighbor; Hashimoto et al. [37] used the distance to the third nearest neighbor; Perez et al. [67] used the distance to the fifth nearest neighbor), or 2) counting the number of galaxies to a fixed absolute magnitude within a fixed volume [4, 10, 11, 12, 41, 42, 46]. Whether cluster membership or local galaxy density is the more fundamental environmental parameter is still under debate.

For example, Dressler [28] observed that morphological type was correlated with both clustercentric distance and local galaxy surface density (calculated using the 10 nearest [projected] neighbors). Illustrated in Figure 2 (Dressler [28] Figure 6), he finds that when considering six moderately irregular clusters in particular, galaxy morphological type is more cleanly related to local galaxy surface density than to clustercentric distance. However, Whitmore & Gilmore [91] reexamined his data and found that morphological fractions varied as much with clustercentric distance as with local galaxy density, and concluded that the density-morphology relation is caused by the relationship between clustercentric radius and local density.

Both cluster membership and local galaxy density have also been used to examine whether galaxy SFR is related to environment [37, 34]. Hashimoto et al. [37] compare the relationship between SFR and local galaxy density (using the third nearest neighbor) in field galaxies and in cluster galaxies. The authors find that at high levels of star formation, the SFR depends on local

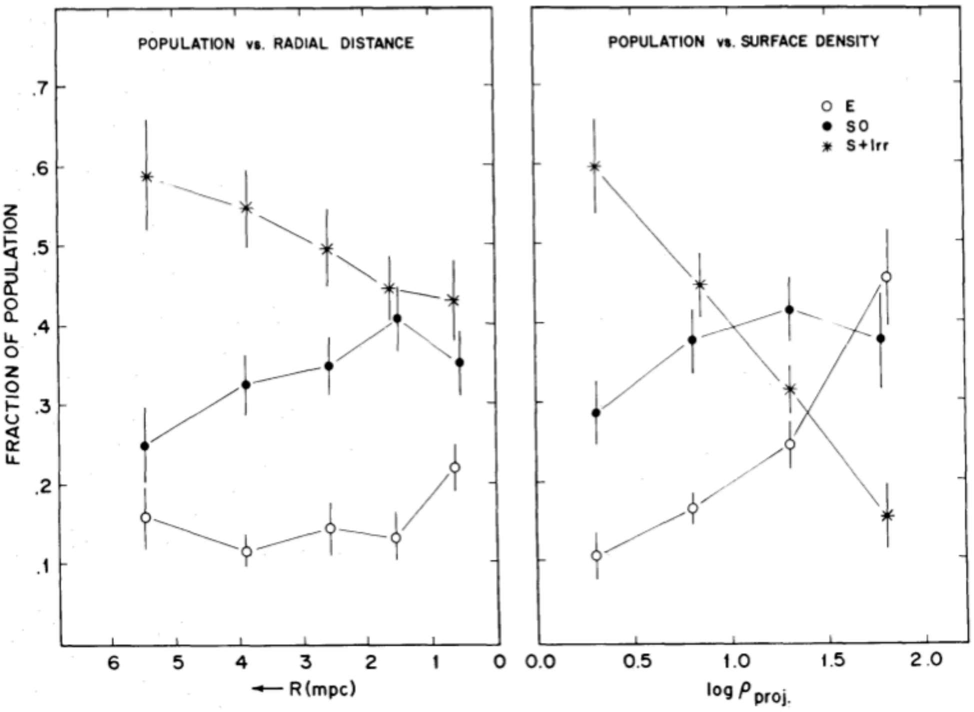

Figure 2: Figure 6 from Dressler [28]. Morphological type is correlated with both clustercentric distance and local galaxy surface density, although for the six irregular clusters used in this figure, morphological type is more cleanly related to local galaxy surface density.

galaxy density whether or not the galaxy is a cluster member, but that at low levels of star formation, the SFR varies with local density only in cluster galaxies.

Kauffmann et al. [46] use a different local density measure to examine the relationship between SFR and local density. They find that SFR is related to local density as measured by counting the number of galaxies within a projected radius of 2 Mpc and ± 500 km s^{-1}. Further, they find that the relationship between SFR and the local density within 1 Mpc is very strong, while the SFR is only weakly correlated with the local density measured within 5 Mpc. Blanton et al. [11] examined at what scale galaxy environment affects galaxy properties, using galaxy counts within several projected radii ranging from 0.2-6.0 h^{-1} Mpc. They find that the fraction of blue galaxies is affected by overdensity on all scales $\leq$1 h^{-1} Mpc, but overdensity on larger scales (6 Mpc) does not independently relate to galaxy color. They conclude that the contrasting Balogh et al. [4] result, that the fraction of star-forming galaxies depends on the galaxy density on scales of both 1.1 Mpc and 5.5 Mpc, may have been because Balogh et al. [4] introduced noise by only counting galaxies to a brighter magnitude limit. The virial radius of cluster halos is about 1-2 h^{-1} Mpc, so the Blanton et al. [11] result indicates that the halo in which a galaxy resides may be an important factor in determining galaxy color and SFR, and possibly also the smaller-scale density.

I have also considered the question of whether local density or cluster membership is important at low redshift (z $\leq$ 0.2) using cosmological simulations discussed in Cen [20]. These are performed using the adaptive mesh refinement (AMR) Eulerian hydrodynamical code *Enzo* [14, 62, 45]. Cen [20] first ran a low resolution simulation with a periodic box of 120 h^{-1} Mpc on a

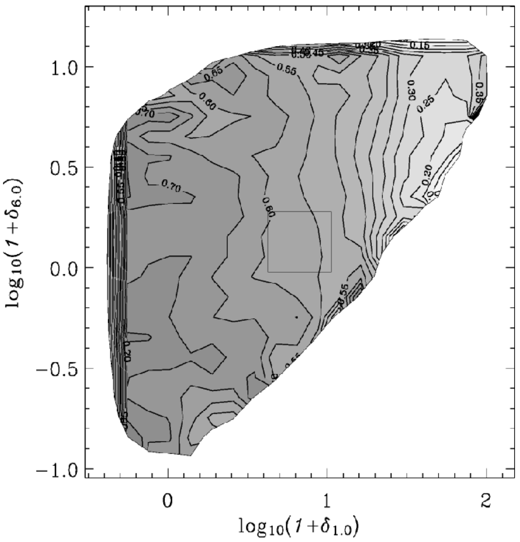

Figure 3: Figure 10 from Blanton et al. [11]. Contours and gray scale show the blue galaxy fraction as a function of local density on 1 and 6 h^{-1} Mpc scales. The vertical contours show that only the local density on the smaller scale is important.

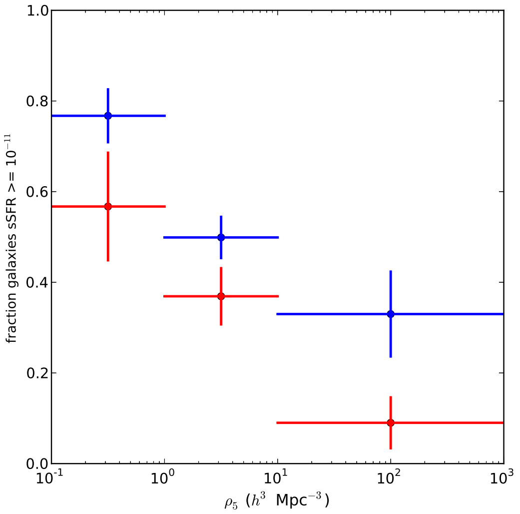

Figure 4: Fraction of star-forming galaxies as a function of local density (ρ_5), for galaxies in a cluster (red) and outside a cluster (blue). Star-forming fraction is a function of local density for galaxies both inside and outside of clusters, but at a single local density galaxies in a cluster are less likely to be star-forming.

side, and then resimulated a region around a cluster with high resolution (0.46 h^{-1} kpc), but embedded within the outer 120 h^{-1} Mpc box. The cluster refined region is 21 $\times$ 24 $\times$ 20 h^{-3} Mpc^3. The central cluster is $\sim$2 $\times$ 10^{14} M$_\odot$ with a virial radius (r$_{200}$) of 1.3 h^{-1} Mpc. This high-resolution box is much larger than the cluster at its center, so there are galaxies at a range of local densities. For details on this simulation, see Tonnesen & Cen [86].

I identify the center of the large cluster in this simulation as the position of the cD galaxy, and use a simple distance criterion to determine if a galaxy may be affected by the cluster–2 Abell radii (3 h^{-1} Mpc), which is slightly larger than 2 r$_{vir}$. The other galaxies in this box may be isolated or associated with smaller groups. I also determine the local galaxy density using the 3-dimensional distance to the fifth nearest neighbor,

$$\rho_5 = \frac{5}{\frac{4}{3}\,\pi\, d_5^3} \tag{3.1}$$

where d_5 is the distance to the fifth nearest neighbor.

I plot the fraction of star-forming galaxies, as defined by galaxies with a specific SFR (sSFR, SFR/M$_*$) greater than or equal to 10^{-11} yr^{-1} [39], as a function of ρ_5 for galaxies both inside and outside of the cluster (split at 2 r$_{Abell}$). The horizontal lines show the width of the ρ_5 bins, and the vertical lines denote the 95% confidence limits. In order to make as fair a comparison as possible, within each ρ_5 bin I match the distributions of the galaxy masses and local densities in both samples. In a KS test, this results in P values for the mass and local density distributions of 0.9 and 0.77, 0.85 and 0.96, and 0.99 and 0.99 respectively within each bin in order of increasing local density. Also, within each sample (inside and outside the cluster), the KS test P value of the mass distributions was at or above 0.68 when comparing the three density bins.

Figure 4 shows that both inside and outside of the cluster, the star-forming fraction decreases with increasing local density. However, at the same local density galaxies in clusters are less likely to be star-forming than galaxies that do not reside in such a massive halo. This supports the Blanton et al. [11] conclusion that the mass of the halo in which a galaxy resides is important, and specifically indicates that smaller-scale density is also important. Considering a galaxy's environment both in terms of cluster membership and local galaxy density is important to understanding how environment affects galaxy sSFR (and therefore color).

4. Focusing on Interactions in Galaxy Clusters

Despite the fact that clusters contain only ∼5% of galaxies [2], they are useful environments to examine carefully for several reasons. For example, focusing on clusters allows observers to examine more galaxies in a single field of view. Also, as I discussed above, clusters have a wide range of local environments. In addition, galaxies are moving quickly relative to each other and to the intracluster medium (ICM), so there are many interactions with shorter interaction timescales than in the field. Finally, clusters contain both the most massive and the least massive galaxies.

The smooth change in the galaxy population from the center of clusters to the field indicates that any processes transforming galaxy color and/or morphology act across a range of environmental densities (or across a range of cluster radii). As I discuss the different types of interactions that can affect galaxies within the cluster environment, I will comment on where in a cluster they are the most effective drivers of galaxy evolution. Evolutionary mechanisms can be split into two broad types: 1) gravitational interactions that affect both gas and stars, and 2) galaxy-ICM interactions that only affect the gas in a galaxy.

4.1 Gravitational Interactions

Gravitational interactions can occur between a galaxy and the cluster potential or between galaxies. The interaction between a galaxy and the cluster potential can strip mass from the galaxy down to the tidal truncation radius [53, 35]. The truncation radius can be expressed as:

$$r_t \sim \frac{\sigma_g}{\sigma_c} r_p \tag{4.1}$$

where r_t is the tidal radius, and r_p is the pericenter of the galaxy's orbit [35]. A simple examination of this equation shows that tidal truncation due to the cluster potential will only occur in the central regions of a cluster–at 250 kpc from the cluster center a galaxy with a velocity dispersion of 200 km s^{-1} will only be truncated to about 50 kpc. Byrd & Valtonen [18] found that the cluster potential can also perturb a galaxy, tidally-triggering SF out to about three times the core radius of a cluster.

Galaxy-galaxy interactions can occur at all cluster radii. One type of galaxy-galaxy interaction is mergers between galaxies with low relative velocities [6]. Generally, merging is unlikely due to the high velocity dispersion in clusters (see discussion in Oemler, Dressler & Butcher [65]). Galaxy harassment is a process in which the fast relative velocities between cluster galaxies result in a number of fly-bys which can disturb or strip mass from a galaxy [54]. Moore et al. [54, 56] found that harassment does not affect a system as dense as a giant elliptical or spiral bulge, so claimed that this transformation process will most strongly affect pure disk galaxies. Galaxy-galaxy interactions can affect both the gas and stellar mass of a galaxy, and can also drive a burst of star formation that may consume any gas remaining in the galaxy [7, 32, 56].

4.2 Galaxy-Intracluster Medium Interactions

Galaxy-ICM interactions are ones in which the gas in a galaxy interacts with the ambient intracluster hot gas. Therefore, these interactions most strongly affect galaxies near the center of clusters, where the ICM is the most dense. Most of these interactions also depend on the velocity difference between the galaxy and the ICM–which also increases as galaxies near the cluster center.

One such process is ram pressure stripping (RPS), which removes the interstellar medium (ISM) of a galaxy as it moves through the ICM by momentum transfer [36]. Ram pressure strength depends on both the ICM density and the relative velocity between the galaxy and the ICM.

$$P_{ram} = \rho_{ICM} v_{diff}^2 \tag{4.2}$$

In order for ram pressure to remove gas from the disk, it must overcome the gravitational force binding gas to the galaxy, calculated as the restoring force per unit area of the disk:

$$F_{grav} = 2\pi G \Sigma_{star} \Sigma_{gas} \tag{4.3}$$

Ram pressure could also compress the gas within a galaxy to increase the SFR in gas that has not been stripped [33].

A galaxy can also be continuously stripped of gas; by, for example, thermal evaporation, Kelvin-Helmholtz instabilties, or turbulent viscous stripping [24, 21, 61]. Any of these continuous stripping processes can act independently from RPS. Cowie & Songaila [24] found that galactic gas can be evaporated at either the unsaturated (in a high density or cool ICM) or saturated (in a low density or hot ICM) rates calculated by Cowie & McKee [23]. The Kelvin-Helmholtz instability occurs when velocity shear is present at the interface of two fluids [21, 1]. The timescale for cloud (or galaxy) destruction is the timescale for the growth of the unstable mode that is the size of the cloud. Finally, Nulsen [61] calculated the maximal mass-loss rate for any cloud using a momentum conservation argument, and called the process turbulent viscous stripping. Any of these processes are unlikely to entirely strip a galaxy of gas–at least not quickly. However, these processes can also aid in mixing gas that has been stripped from the galaxy by ram pressure into the ICM.

Although I have discussed galaxy-ICM interactions in terms of stripping gas from a galactic disk, they can also remove gas from the larger gas halo surrounding the galaxy. Starvation, the removal of the outer gas envelope by the ICM, can result in normal star formation slowly exhausting the gas reservoir in the galaxy disk [51].

5. Morphological Evolution from Spiral to S0

Thus far, I have focused on the color or SFR of galaxies; for example, the scatter in the galaxy color-magnitude diagram and the Butcher-Oemler effect. However, there is a large amount of evidence that the reddening of galaxies in clusters and dense environments reflects the morphological

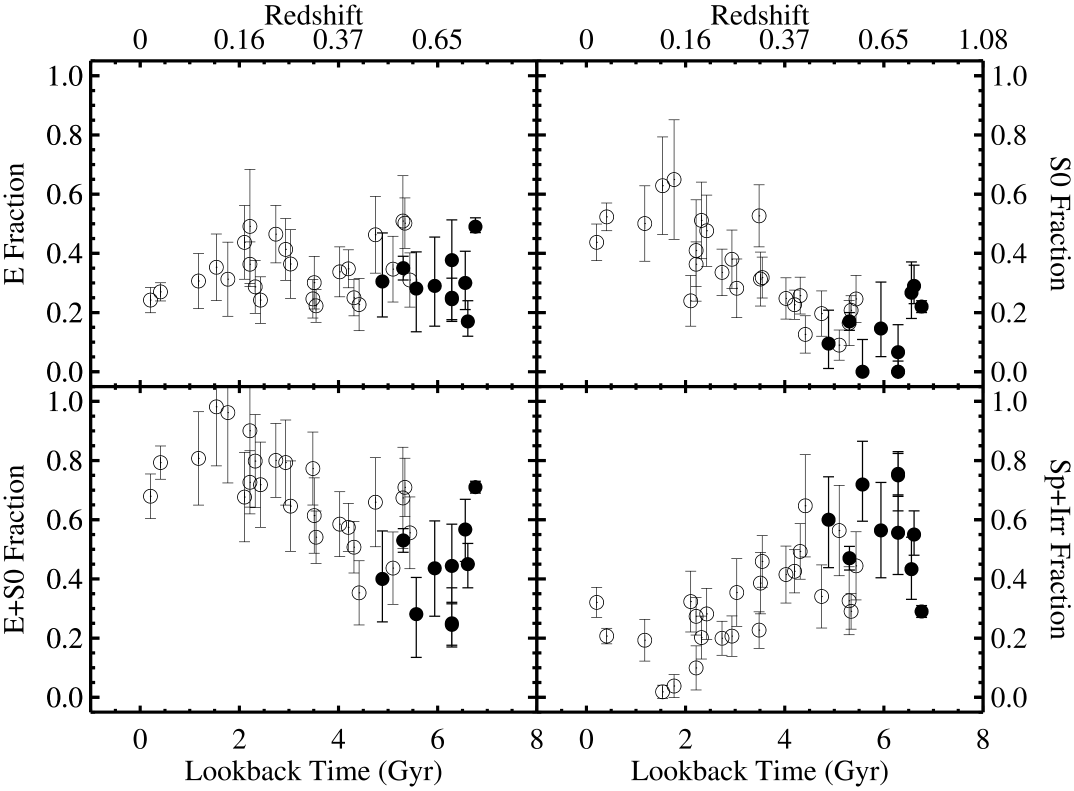

Figure 5: Figure 3 from Desai et al. [27]. As the Sp+Irr fraction of cluster galaxies (within a radius of 600 kpc using the classic cosmology) decreases, the S0 fraction increases and the E fraction remains constant at these redshifts.

evolution of spiral galaxies into S0s. The spiral to S0 ratio decreases with redshift [29, 31, 69, 27]. Desai et al. [27] consider the E, S0, and spiral fraction in clusters out to $z > 1$ (shown in Figure 5), and find that as the spiral fraction decreases, the S0 fraction increases while the elliptical fraction in clusters remains constant. They find that this evolution in morphological fraction begins at $z \sim 0.4$.

In order for a spiral to evolve into an S0, both spectroscopic and morphological changes must take place: the galaxy must become red, it must lose spiral structure in its disk, and the bulge-to-disk ratio must increase.

A simple way for a galaxy to become red is for it to lose its fuel for star formation, and there is strong evidence of pure gas removal in cluster galaxies. In fact, van den Bergh [88] proposed a new galaxy classification system that included “anemic" spirals, gas-poor spirals with low SFRs, and found that these anemic spirals were more frequently found in clusters (also called passive spirals in, e.g. [58, 68]). Poggianti et al. [68] found that at high redshifts the majority of poststarburst galaxies are morphologically identified as spirals, and concluded that the mechanism transforming galaxy color affects only the gas in the galaxies. Solanes et al. [77] studied HI deficiency in 18 clusters and found that HI deficiency–defined by Haynes & Giovanelli [38] as $log_{10}(M_{HI}\ observed/M_{HI}\ expected)$, where $M_{HI}\ expected$ is based on a sample of isolated spirals of the same morphology and optical radius–decreases smoothly out to large projected distances from cluster centers. The nearby Virgo cluster has been studied in much detail, and the spirals in the center of that cluster have smaller HI disks than stellar disks [19, 89]. Koopmann & Kenney [50] find that the reduced massive SFR in Virgo galaxies is linked the the truncation of their star-forming disks.

A galaxy-ICM interaction is the likely mechanism forming passive (or anemic) spirals, because they have had their gas removed but are morphologically spirals (so their stellar disks are relatively undisturbed). If passive spirals are precursors to S0s, then a galaxy-ICM interaction is at least part of the process driving the evolution of normal spirals into S0s. Moran et al. [57] used a simple argument to show that if the passive spiral fraction in Cl 0024+17 was universal at z=0.4, assuming all passive spirals become S0s is consistent with the S0 fraction at z=0.

In a detailed study of the passive spirals and S0s in two intermediate redshift clusters, Moran et al. [58] found that passive spirals were well-fit by stellar population models that input either the gradual cessation of star formation (by, for example, starvation), or a rapid truncation of star formation (by, for example, RPS of the disk gas). The S0s in the clusters also fit these star formation histories, indicating the populations were related. Further, the galaxies undergoing starvation tended to be infalling in groups and the galaxies with truncated star formation were near the centers of the clusters, so the transformation scenario was related to the surrounding ICM. This strongly indicated that passive spirals turn into S0s, and that galaxy-ICM interactions play a large role in that transformation.

The second component in the transformation of a spiral into an S0 is the loss of spiral structure. This can also be a result of gas loss alone. Bekki et al. [8] used simulations to show that if gas is no longer accreted by a galaxy, it will lose its spiral arms in about 3.5 Gyr. This is in good agreement with observational and model estimates for how long morphological transformation may take (e.g [49, 68]). However, as discussed above, Moran et al. [58] found similar stellar populations in passive spirals and S0s, indicating that a faster mechanism was driving morphological evolution.

Finally, I consider the necessary increase in the bulge-to-disk (B/D) ratio. This step can be the result of: 1) growing the bulge, or 2) fading the disk. It seems likely that interactions between galaxies are necessary to grow the bulge of a spiral galaxy, while only gas removal or exhaustion is necessary to fade the disk. Observations have shown that there are S0s in clusters that were likely created by each of these processes [22, 57].

Fading the disk of a galaxy with a B/D = 0.2 will result in a galaxy with a B/D = 0.5, so pure gas removal can turn an Sb galaxy into an S0 galaxy [33, 78]. Solanes et al. [78] find that the bulge luminosities of Sa galaxies are similar to those of S0s, and all types have a range of luminosities, so it is not universally necessary to increase the bulge luminosity to transform a spiral to an S0. However, if the slow fading of the disk was the mechanism at work, the total luminosity of S0s should be less than that of spirals, which is not generally the case [28, 16]. The models of Kodama & Smail [49] indicate that if the evolution of spirals is responsible for the increase in the S0 fraction, all spirals would have to become S0s, even Sc-Sd galaxies with small bulges. For most of these disk-dominated galaxies to become S0s there would have to be bulge growth.

What can grow the bulge of a spiral galaxy? Galaxy harassment can drive instabilities that will heat the disk and result in gas flowing to the galaxy center, which can grow the bulge of a galaxy [55, 56, 32]. Moran et al. [58] find that S0s in Cl 0024+17, a cluster with a recent assembly history, show more kinematic disturbance, indicating that galaxy harassment is one of the mechanisms transforming spirals into S0s. Unequal-mass mergers can also grow the bulge of a spiral galaxy without completely destroying the disk [7]. Fujita & Nagashima [33] find that ram pressure can increase the SFR of a galaxy, and while strong ram pressure will lower the SFR in the disk by removing HI, it will not strip gas from the galaxy center, so star formation will continue. If, as in Schulz & Struck [74] and Tonnesen & Bryan [84], dense gas in the disk that is not immediately stripped will spiral towards the center, the bulge may grow slightly more than just from star formation of the gas that originated in the galaxy center while the disk fades. However, RPS would grow the bulge the least of any of these processes.

5.1 Star Formation in the Disk of a Ram Pressure Stripped Galaxy

While many interactions occur in clusters (galaxy-galaxy, galaxy-cluster, and galaxy-ICM interactions), it is worthwhile to study individual types of interactions in isolation in order to constrain the effects of a single type of interaction. In Tonnesen & Bryan [82], we use the AMR code *Enzo* [14, 60, 62] to run a set of high resolution simulations (38 pc resolution, which is small enough to marginally resolve giant molecular clouds). Here I will discuss our goal to understand whether ram pressure can induce star formation in a galactic disk, producing starburst galaxies or increasing the mass of the bulge.

As discussed in detail in Tonnesen & Bryan [82, 83, 84], the simulation includes radiative cooling using the Sarazin & White [73] cooling curve extended to low temperatures ($T_{\rm min} = 300$ K) as described in Tasker & Bryan [81]. This allows cool, dense gas to form in the galaxy and generates a clumpy, multiphase ISM [81, 84].

In Tonnesen & Bryan [82], star formation occurred when two criteria were met: 1) the gas density in a cell exceeded a critical overdensity (3.85×10^{-25} g cm^{-3}), and 2) the gas temperature was below 1.1×10^4 K. The implementation of star formation and feedback is explained in detail in Tasker & Bryan [81] and in Tonnesen & Bryan [82].

We model a massive spiral galaxy with a flat rotation curve of 200 km s^{-1}. It consists of a gas disk that is followed using the AMR algorithm (including self-gravity of the gas and any newly formed stars), as well as the static potentials of the (pre-existing) stellar disk, stellar bulge, and dark matter halo [72, 82, 83, 84, 85].

In Tonnesen & Bryan [82] we compare the star formation in the disks of two simulations. They both begin with the same galaxy density profiles evolving in a static ICM. SFNW (Star Formation No Wind) evolves in a static ICM, while SFW (Stfar Formation Wind) initially evolves in a static ICM and is later (t∼210 Myr) stripped by a higher-density ICM wind.

We define the disk to extend 2 kpc from the the central disk plane, which includes all of the star formation in the SFNW run. First, in the top panel of Figure 6 (Figure 1 of Tonnesen & Bryan [82]) we plot the SFR as a function of time for the SFNW and SFW runs. For the first 220 Myr the SFRs are nearly identical. Shortly after the ICM wind hits the SFW galaxy disk, its SFR drops precipitously. RPS quickly lowers the SFR and does not induce even a short-lived burst of star formation (at least at the level of ram pressure modeled here).

In the bottom panel of Figure 6 we plot the radius including 95% of the new stars formed in the disk against time. As in the panel above, we find that the two cases are nearly identical for the first 200 Myr. However, it takes until ∼290 Myr for the star-formation radii to diverge. This is

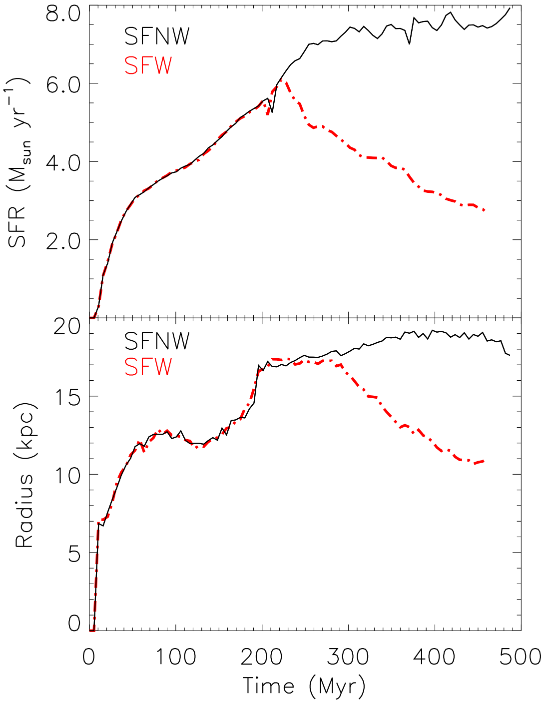

Figure 6: Top panel: SFR as a function of time in the run with no wind (SFNW, black line) and with an ICM wind after ∼210 Myr (SFW, red line). ∼10 Myr after the wind hits the disk, the SFR of SFW begins decreasing, and continues to decrease as gas is stripped. Bottom panel: the disk radius that includes 95% of the new stars formed as a function of time. The star forming radius of SFW decreases later than the SFR, probably because some dense clouds in the disk cannot be stripped by the wind, so form stars.

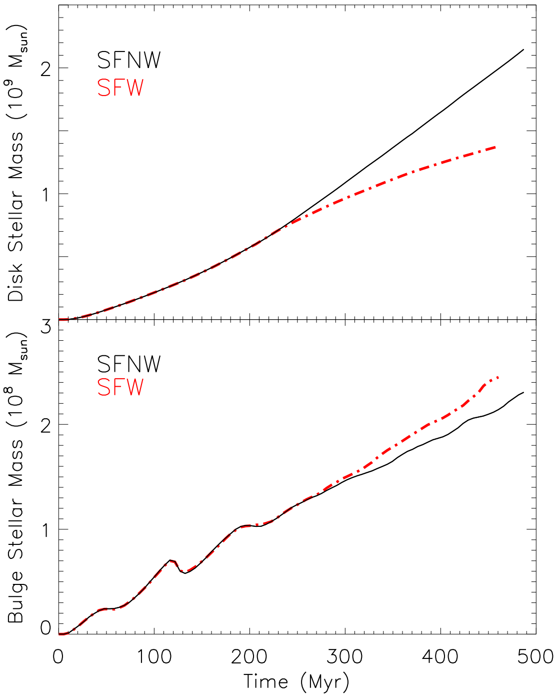

Figure 7: Top panel: Total amount of stellar mass formed in the disk (i.e. within 2 kpc of the disk plane), as a function of time. Shortly after the wind hits SFW, the SFR decreases. Bottom panel: the mass of newly formed bulge stars as a function of time. Ram pressure does lead to more stars in the bulge (all stars within 3.4 kpc of the galaxy center). However, the difference does not significantly change the B/T ratio, which begins at 0.1 with M_{Bulge} = 10^{10} $M_\odot$ and M_{Disk} = 10^{11} $M_\odot$.

likely because dense clouds have formed up to 17 kpc from the disk center that cannot be instantly stripped by the ICM wind. It is only after these clouds have formed stars or been destroyed or stripped by the ICM wind that the star-formation radius drops. Ram pressure is affecting the outer disk, resulting in a dimmer, less massive disk.

We also consider the total amount of newly formed stellar mass in the disk and in the bulge of the galaxy. As shown in the top panel of Figure 7 (Figure 4 in Tonnesen & Bryan [82]), the total stellar mass formed in the disk, since the beginning of the simulation, is nearly identical in SFNW and SFW for the first 200 Myr, but once the wind hits the disk, the two lines begin to diverge.

If we focus only on the bulge stars formed since the simulation began in a sphere with a 3.4 kpc radius from the galaxy center (this includes 80% of the mass in the spherical Hernquist bulge we initially used to determine our galaxy potential [40]), we find that including the wind leads to more stars in the galactic bulge, as shown in the bottom panel of Figure 7. As discussed in Tonnesen & Bryan [84], gas clouds that are not stripped are able to spiral towards the center of the disk due to a loss of angular momentum by drag from the ICM (initially seen by Schulz & Struck [74]). It is this inflow of gas within the disk that adds most of the stars to the bulge (rather than stellar fallback).

The bulge-to-total ratio of new stars is 0.1 in the SFNW galaxy and 0.2 in the SFW galaxy. However, the galaxy initially had a stellar disk mass of 10^{11} $M_{\odot}$ and a stellar bulge mass of 10^{10} $M_{\odot}$, so the new stars change the bulge-to-total ratio of stellar mass by at most a few percent. As expected, ram pressure is more effective at fading the galaxy disk than at growing the bulge. However, this conclusion may depend somewhat on our disk model. First, if our galaxy was much less massive, then we might expect the disk to be even more quickly stripped and to dim faster, while the bulge growth may remain very similar. This could affect the bulge-to-disk ratio. Later-type galaxies do tend to be less massive and are the very galaxies for which it is most important that the bulge mass grows in order to produce an S0 [78]. At this ram pressure strength, the galaxy would have to have 2 orders of magnitude less stellar mass for the difference in star formation to have a significant effect on the bulge-to-total mass ratio.

In summary, based on both the observations and simulations discussed in this section, it is likely that RPS alone can slowly transform spirals into S0s that are less luminous than their spiral parents. Gravitational mechanisms can also cause galaxies to lose or consume their gas, and may be more effective at growing the bulge. However, a galaxy disk will certainly survive a galaxy-ICM interaction, which is a necessary constraint on the mechanism driving this morphological evolution.

6. Summary and Future Prospects

In this proceedings, I have discussed the evidence that environment affects galaxy properties, and looked in detail at the scales at which the environment affects galaxies. I have outlined the different environmental mechanisms that can act on cluster galaxies and then focused on the morphological evolution of spirals into S0s. Finally, I focused on work by Tonnesen & Bryan [82] that examined how RPS can affect star formation in galactic disks and bulges. I summarize the main points below:

1) Galaxies in dense environments are more likely to be red. Low-mass galaxies are likely red due to environmental affects (Section 3 and Figure 1).

2) The local environment of galaxies is correlated with galaxy properties such as color, up to the scale of the halo in which a galaxy resides (Section 3.1 and Figures 3 & 4).

3) The color evolution of galaxies from blue to red is likely closely tied to the morphological evolution of galaxies from spirals to S0s (Section 5 and Figure 5).

4) While gas loss alone can drive the evolution of a spiral into an S0 (Section 5), RPS seems unable to grow the bulge enough transform most of the higher redshift cluster spiral population into the local S0 population (Section 5.1 and Figures 6 & 7). It is much more effective at fading the disk than at growing the bulge.

In Section 5 I summarized some of the work examining the mechanisms that can transform spirals into S0s, with a definite focus on the role of gas loss or ram pressure stripping. However, it is worth reiterating that there are many interactions that occur in clusters and groups that could drive the evolution of spirals into S0s. For example, while RPS is a straightforward way to create anemic, or passive, spirals, it may not be the only mechanism that can remove gas without entirely destroying spiral structure in the disk. Detailed observations of the kinematics of the disks of passive spirals in a range of environments–e.g. the centers and outskirts of low- and high-mass clusters–may be used to determine the impact, and likelihood, of gravitational interactions (similar to the work of Moran et al. [58, 59]). In addition, more work can be done to compare the stellar populations of spirals, passive spirals, and S0s to resolve the conflicting timelines of the transformations in Poggianti et al. [68] and Moran et al. [58]. Further, examinations of the kinematics of S0 bulges in a range of environments may be used to distinguish between growth through unequal-mass mergers, which may grow more classical bulges, and growth through gas inflow or excess star formation from harassment or RPS, which may be more likely to grow a psuedobulge.

There is certainly much more work that can be done to examine galaxy evolution in dense environments, and as hydrodynamical cosmological simulations continue to increase their resolution they can also be used to look in detail at both the color and morphological evolution of cluster galaxies.

References

[1] Agertz, O., Moore, B., Stadel, J., Potter, D., Miniati, F., Read, J., Mayer, L., Gawryszczak, A., Kravtsov, A., Nordlund, Å., Pearce, F., Quilis, V., Rudd, D., Springel, V., Stone, J., Tasker, E., Teyssier, R., Wadsley, J., and Walder, R.: 2007, *Monthly Notices of the Royal Astronomical Society* **380**, 963.

[2] Bahcall, N.A.: 1996, *ArXiv Astrophysics e-prints*, arXiv:astro-ph/9611148.

[3] Baldry, I.K., Glazebrook, K., Brinkmann, J., Ivezić, Ž., Lupton, R.H., Nichol, R.C., and Szalay, A.S.: 2004, *Astrophys. J.* **600**, 681.

[4] Balogh, M., Eke, V., Miller, C., Lewis, I., Bower, R., Couch, W., Nichol, R., Bland-Hawthorn, J., Baldry, I.K., Baugh, C., Bridges, T., Cannon, R., Cole, S., Colless, M., Collins, C., Cross, N., Dalton, G., de Propris, R., Driver, S.P., Efstathiou, G., Ellis, R.S., Frenk, C.S., Glazebrook, K., Gomez, P., Gray, A., Hawkins, E., Jackson, C., Lahav, O., Lumsden, S., Maddox, S., Madgwick, D., Norberg, P., Peacock, J.A., Percival, W., Peterson, B.A., Sutherland, W., and Taylor, K.: 2004, *Monthly Notices of the Royal Astronomical Society* **348**, 1355.

[5] Balogh, M.L., Pearce, F.R., Bower, R.G., and Kay, S.T.: 2001, *Monthly Notices of the Royal Astronomical Society* **326**, 1228.

[6] Barnes, J.E. and Hernquist, L.E.: 1991, *Astrophys. J.* **370**, L65.

[7] Bekki, K.: 1998, *Astrophys. J.* **502**, L133.

[8] Bekki, K., Couch, W.J., and Shioya, Y.: 2002, *Astrophys. J.* **577**, 651.

[9] Binney, J.: 1977, *Astrophys. J.* **215**, 492.

[10] Blanton, M.R., Eisenstein, D., Hogg, D.W., Schlegel, D.J., and Brinkmann, J.: 2005, *Astrophys. J.* **629**, 143.

[11] Blanton, M.R., Eisenstein, D., Hogg, D.W., and Zehavi, I.: 2006, *Astrophys. J.* **645**, 977.

[12] Blanton, M.R., Hogg, D.W., Bahcall, N.A., Baldry, I.K., Brinkmann, J., Csabai, I., Eisenstein, D., Fukugita, M., Gunn, J.E., Ivezić, Ž., Lamb, D.Q., Lupton, R.H., Loveday, J., Munn, J.A., Nichol, R.C., Okamura, S., Schlegel, D.J., Shimasaku, K., Strauss, M.A., Vogeley, M.S., and Weinberg, D.H.: 2003, *Astrophys. J.* **594**, 186.

[13] Brooks, A.M., Governato, F., Quinn, T., Brook, C.B., and Wadsley, J.: 2009, *Astrophys. J.* **694**, 396.

[14] Bryan, G.L.: 1999, *Comput. Sci. Eng., Vol. 1, No. 2, p. 46 - 53* **1**, 46.

[15] Bundy, K., Scarlata, C., Carollo, C.M., Ellis, R.S., Drory, N., Hopkins, P., Salvato, M., Leauthaud, A., Koekemoer, A.M., Murray, N., Ilbert, O., Oesch, P., Ma, C.-P., Capak, P., Pozzetti, L., and Scoville, N.: 2010, *Astrophys. J.* **719**, 1969.

[16] Burstein, D., Ho, L.C., Huchra, J.P., and Macri, L.M.: 2005, *Astrophys. J.* **621**, 246.

[17] Butcher, H. and Oemler, A., Jr.: 1978, *Astrophys. J.* **226**, 559.

[18] Byrd, G. and Valtonen, M.: 1990, *Astrophys. J.* **350**, 89.

[19] Cayatte, V., van Gorkom, J.H., Balkowski, C., and Kotanyi, C.: 1990, *The Astronomical Journal* **100**, 604.

[20] Cen, R.: 2010, *ArXiv e-prints*, arXiv:1010.5014.

[21] Chandrasekhar, S.: 1961, *International Series of Monographs on Physics, Oxford: Clarendon, 1961*.

[22] Christlein, D. and Zabludoff, A.I.: 2004, *Astrophys. J.* **616**, 192.

[23] Cowie, L.L. and McKee, C.F.: 1977, *Astrophys. J.* **211**, 135.

[24] Cowie, L.L. and Songaila, A.: 1977, *Nature* **266**, 501.

[25] de Vaucouleurs, G.: 1962, *Problems of Extra-Galactic Research* **15**, 3.

[26] de Vaucouleurs, G.: 1960, *The Astronomical Journal* **65**, 51.

[27] Desai, V., Dalcanton, J.J., Aragón-Salamanca, A., Jablonka, P., Poggianti, B., Gogarten, S.M., Simard, L., Milvang-Jensen, B., Rudnick, G., Zaritsky, D., Clowe, D., Halliday, C., Pelló, R., Saglia, R., and White, S.: 2007, *Astrophys. J.* **660**, 1151.

[28] Dressler, A.: 1980, *Astrophys. J.* **236**, 351.

[29] Dressler, A., Oemler, A., Jr., Couch, W.J., Smail, I., Ellis, R.S., Barger, A., Butcher, H., Poggianti, B.M., and Sharples, R.M.: 1997, *Astrophys. J.* **490**, 577.

[30] Fall, S.M. and Efstathiou, G.: 1980, *Monthly Notices of the Royal Astronomical Society* **193**, 189.

[31] Fasano, G., Poggianti, B.M., Couch, W.J., Bettoni, D., Kjærgaard, P., and Moles, M.: 2000, *Astrophys. J.* **542**, 673.

[32] Fujita, Y.: 1998, *Astrophys. J.* **509**, 587.

[33] Fujita, Y. and Nagashima, M.: 1999, *Astrophys. J.* **516**, 619.

[34] Gómez, P.L., Nichol, R.C., Miller, C.J., Balogh, M.L., Goto, T., Zabludoff, A.I., Romer, A.K., Bernardi, M., Sheth, R., Hopkins, A.M., Castander, F.J., Connolly, A.J., Schneider, D.P., Brinkmann, J., Lamb, D.Q., SubbaRao, M., and York, D.G.: 2003, *Astrophys. J.* **584**, 210.

[35] Gnedin, O.Y.: 2003, *Astrophys. J.* **589**, 752.

[36] Gunn, J.E. and Gott, J.R., III: 1972, *Astrophys. J.* **176**, 1.

[37] Hashimoto, Y., Oemler, A., Jr., Lin, H., and Tucker, D.L.: 1998, *Astrophys. J.* **499**, 589.

[38] Haynes, M.P. and Giovanelli, R.: 1984, *The Astronomical Journal* **89**, 758.

[39] Heinis, S., Budavári, T., Szalay, A.S., Arnouts, S., Aragón-Calvo, M.A., Wyder, T.K., Barlow, T.A., Foster, K., Peter, F.G., Martin, D.C., Morrissey, P., Neff, S.G., Schiminovich, D., Seibert, M., Bianchi, L., Donas, J., Heckman, T.M., Lee, Y.-W., Madore, B.F., Milliard, B., Rich, R.M., and Yi, S.K.: 2009, *Astrophys. J.* **698**, 1838.

[40] Hernquist, L.: 1993, *The Astrophysical Journal Supplement Series* **86**, 389.

[41] Hogg, D.W., Blanton, M.R., Brinchmann, J., Eisenstein, D.J., Schlegel, D.J., Gunn, J.E., McKay, T.A., Rix, H.-W., Bahcall, N.A., Brinkmann, J., and Meiksin, A.: 2004, *Astrophys. J.* **601**, L29.

[42] Hogg, D.W., Blanton, M.R., Eisenstein, D.J., Gunn, J.E., Schlegel, D.J., Zehavi, I., Bahcall, N.A., Brinkmann, J., Csabai, I., Schneider, D.P., Weinberg, D.H., and York, D.G.: 2003, *Astrophys. J.* **585**, L5.

[43] Hubble, E.P.: 1926, *Astrophys. J.* **64**, 321.

[44] Hubble, E. and Humason, M.L.: 1931, *Astrophys. J.* **74**, 43.

[45] Joung, M.R., Cen, R., and Bryan, G.L.: 2009, *Astrophys. J.* **692**, L1.

[46] Kauffmann, G., White, S.D.M., Heckman, T.M., Ménard, B., Brinchmann, J., Charlot, S., Tremonti, C., and Brinkmann, J.: 2004, *Monthly Notices of the Royal Astronomical Society* **353**, 713.

[47] Kereš, D., Katz, N., Fardal, M., Davé, R., and Weinberg, D.H.: 2009, *Monthly Notices of the Royal Astronomical Society* **395**, 160.

[48] Kereš, D., Katz, N., Weinberg, D.H., and Davé, R.: 2005, *Monthly Notices of the Royal Astronomical Society* **363**, 2.

[49] Kodama, T. and Smail, I.: 2001, *Monthly Notices of the Royal Astronomical Society* **326**, 637.

[50] Koopmann, R.A. and Kenney, J.D.P.: 2004, *Astrophys. J.* **613**, 866.

[51] Larson, R.B., Tinsley, B.M., and Caldwell, C.N.: 1980, *Astrophys. J.* **237**, 692.

[52] Melnick, J. and Sargent, W.L.W.: 1977, *Astrophys. J.* **215**, 401.

[53] Merritt, D.: 1984, *Astrophys. J.* **276**, 26.

[54] Moore, B., Katz, N., Lake, G., Dressler, A., and Oemler, A.: 1996, *Nature* **379**, 613.

[55] Moore, B., Lake, G., and Katz, N.: 1998, *Astrophys. J.* **495**, 139.

[56] Moore, B., Lake, G., Quinn, T., and Stadel, J.: 1999, *Monthly Notices of the Royal Astronomical Society* **304**, 465.

[57] Moran, S.M., Ellis, R.S., Treu, T., Salim, S., Rich, R.M., Smith, G.P., and Kneib, J.-P.: 2006, *Astrophys. J.* **641**, L97.

[58] Moran, S.M., Ellis, R.S., Treu, T., Smith, G.P., Rich, R.M., and Smail, I.: 2007, *Astrophys. J.* **671**, 1503.

[59] Moran, S.M., Miller, N., Treu, T., Ellis, R.S., and Smith, G.P.: 2007, *Astrophys. J.* **659**, 1138.

[60] Norman, M.L. and Bryan, G.L.: 1999, *Numerical Astrophysics* **240**, 19.

[61] Nulsen, P.E.J.: 1982, *Monthly Notices of the Royal Astronomical Society* **198**, 1007.

[62] O'Shea, B.W., Bryan, G., Bordner, J., Norman, M.L., Abel, T., Harkness, R., and Kritsuk, A.: 2004, *ArXiv Astrophysics e-prints*, arXiv:astro-ph/0403044.

[63] Ocvirk, P., Pichon, C., and Teyssier, R.: 2008, *Monthly Notices of the Royal Astronomical Society* **390**, 1326.

[64] Oemler, A., Jr.: 1974, *Astrophys. J.* **194**, 1.

[65] Oemler, A., Jr., Dressler, A., and Butcher, H.R.: 1997, *Astrophys. J.* **474**, 561.

[66] Pannella, M., Gabasch, A., Goranova, Y., Drory, N., Hopp, U., Noll, S., Saglia, R.P., Strazzullo, V., and Bender, R.: 2009, *Astrophys. J.* **701**, 787.

[67] Perez, J., Tissera, P., Padilla, N., Alonso, M.S., and Lambas, D.G.: 2009, *Monthly Notices of the Royal Astronomical Society* **399**, 1157.

[68] Poggianti, B.M., Smail, I., Dressler, A., Couch, W.J., Barger, A.J., Butcher, H., Ellis, R.S., and Oemler, A., Jr.: 1999, *Astrophys. J.* **518**, 576.

[69] Postman, M., Franx, M., Cross, N.J.G., Holden, B., Ford, H.C., Illingworth, G.D., Goto, T., Demarco, R., Rosati, P., Blakeslee, J.P., Tran, K.-V., Benítez, N., Clampin, M., Hartig, G.F., Homeier, N., Ardila, D.R., Bartko, F., Bouwens, R.J., Bradley, L.D., Broadhurst, T.J., Brown, R.A., Burrows, C.J., Cheng, E.S., Feldman, P.D., Golimowski, D.A., Gronwall, C., Infante, L., Kimble, R.A., Krist, J.E., Lesser, M.P., Martel, A.R., Mei, S., Menanteau, F., Meurer, G.R., Miley, G.K., Motta, V., Sirianni, M., Sparks, W.B., Tran, H.D., Tsvetanov, Z.I., White, R.L., and Zheng, W.: 2005, *Astrophys. J.* **623**, 721.

[70] Rees, M.J. and Ostriker, J.P.: 1977, *Monthly Notices of the Royal Astronomical Society* **179**, 541.

[71] Robertson, B., Yoshida, N., Springel, V., and Hernquist, L.: 2004, *Astrophys. J.* **606**, 32.

[72] Roediger, E. and Brüggen, M.: 2006, *Monthly Notices of the Royal Astronomical Society* **369**, 567.

[73] Sarazin, C.L. and White, R.E., III: 1987, *Astrophys. J.* **320**, 32.

[74] Schulz, S. and Struck, C.: 2001, *Monthly Notices of the Royal Astronomical Society* **328**, 185.

[75] Silk, J.: 1977, *Astrophys. J.* **211**, 638.

[76] Smith, G.P., Treu, T., Ellis, R.S., Moran, S.M., and Dressler, A.: 2005, *Astrophys. J.* **620**, 78.

[77] Solanes, J.M., Manrique, A., García-Gómez, C., González-Casado, G., Giovanelli, R., and Haynes, M.P.: 2001, *Astrophys. J.* **548**, 97.

[78] Solanes, J.M., Salvador-Sole, E., and Sanroma, M.: 1989, *The Astronomical Journal* **98**, 798.

[79] Sorrentino, G., Antonuccio-Delogu, V., and Rifatto, A.: 2006, *Astron. Astroph.* **460**, 673.

[80] Strateva, I., Ivezić, Ž., Knapp, G.R., Narayanan, V.K., Strauss, M.A., Gunn, J.E., Lupton, R.H., Schlegel, D., Bahcall, N.A., Brinkmann, J., Brunner, R.J., Budavári, T., Csabai, I., Castander, F.J., Doi, M., Fukugita, M., Győry, Z., Hamabe, M., Hennessy, G., Ichikawa, T., Kunszt, P.Z., Lamb, D.Q., McKay, T.A., Okamura, S., Racusin, J., Sekiguchi, M., Schneider, D.P., Shimasaku, K., and York, D.: 2001, *The Astronomical Journal* **122**, 1861.

[81] Tasker, E.J. and Bryan, G.L.: 2006, *Astrophys. J.* **641**, 878.

[82] Tonnesen, S. and Bryan, G.L.: 2011, *submitted to Monthly Notices of the Royal Astronomical Society*

[83] Tonnesen, S. and Bryan, G.L.: 2010, *Astrophys. J.* **709**, 1203.

[84] Tonnesen, S. and Bryan, G.L.: 2009, *Astrophys. J.* **694**, 789.

[85] Tonnesen, S., Bryan, G.L., and Chen, R.: 2011, *Astrophys. J.* **731**, 98.

[86] Tonnesen, S. and Cen, R.: 2011, *ArXiv e-prints*, arXiv:1111.0636.

[87] Treu, T., Ellis, R.S., Kneib, J.-P., Dressler, A., Smail, I., Czoske, O., Oemler, A., and Natarajan, P.: 2003, *Astrophys. J.* **591**, 53.

[88] van den Bergh, S.: 1976, *Astrophys. J.* **206**, 883.

[89] Warmels, R.H.: 1988, *Astronomy and Astrophysics Supplement Series* **72**, 427.

[90] White, S.D.M. and Rees, M.J.: 1978, *Monthly Notices of the Royal Astronomical Society* **183**, 341.

[91] Whitmore, B.C. and Gilmore, D.M.: 1991, *Astrophys. J.* **367**, 64.