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Galaxy Evolution and Environment

Pieter van Dokkum & Ryan Quadri

Yale University

Abstract. The properties of galaxies are strongly correlated with their environment, with red galaxies dominating galaxy clusters and blue galaxies dominating the general field. However, not all field galaxies are young: studies of the colors, line strengths, and M/L ratios of massive early-type galaxies at $0 < z < 1.3$ show that the most massive galaxies do not seem to care about their surroundings, and have very similar ages irrespective of their environment. There is good evidence that the *growth* of these galaxies does continue longer in the field than in clusters, via (nearly) dissipationless mergers of already old galaxies. These results are consistent with predictions of recent galaxy formation models, which incorporate AGN feedback to suppress star formation in the most massive halos. Systematic studies of the relation of galaxies with their environment beyond $z = 1$ are difficult, and still somewhat contradictory. Intriguingly both the DEEP-2 and VVDS surveys find that the color-density relation disappears at $z \sim 1.3$, unfortunately just at the point where both surveys become highly incomplete. On the other hand, clustering studies at $z \sim 2.5$ have shown that red galaxies cluster more strongly than blue galaxies, implying that the color-density relation was already in place at that redshift.

1. Introduction

It has been known for many decades that the properties of galaxies correlate strongly with their environment. Early studies demonstrated that galaxies in rich clusters are usually red and often have early-type morphologies, whereas most galaxies in the general field are blue spiral galaxies. Dressler (1980) showed that the morphology of galaxies is a smoothly varying function of local projected density, setting the stage for many studies over the following decades which quantified this morphology-density relation better and tried to identify the cause, or causes. Weinmann et al. (2006) present what could perhaps be described as the 21$^{\text{st}}$ century version of the morphology-density relation, by quantifying the dependence of galaxy color, star formation rate and morphology on halo mass, using a large sample drawn from the SDSS.

A key question is why there are red galaxies at all. Models suggest that gas should continuously accrete onto halos, shock heat to the virial temperature, and subsequently cool, leading to sustained star formation in a disk and blue colors associated with newly formed stars (e.g., Fall & Efstathiou 1980). The existence of large numbers of apparently ancient galaxies, in particular in rich clusters, is not easily explained in this context. As observations and models have become more and more sophisticated, this 20+ year old problem has not gone away, but instead is the topic of extensive debate.

A partial solution, implemented in semi-analytical models of the 1990s, is to postulate that gas cooling is disrupted (due to ram pressure stripping, harrassment, or other processes) if a galaxy is subsumed in a more massive halo and becomes a satellite (e.g., Kauffmann et al. 1999). This "nurture" solution naturally produces red galaxies in clusters (with the exception of the central galaxy) and blue field galaxies. More recently, other mechanisms were added. In current models star formation is halted when galaxies exceed a critical mass scale ("nature"), even if they are the central galaxy in their halo. This suppression can be due to AGN feedback (e.g., Croton et al. 2006), and/or may occur naturally as a result of virial shocks (Birnboim, Dekel, & Neistein 2007). The observational challenge is to assess the importance of these various proposed nurture and nature mechanisms as a function of mass, environment, and cosmic time.

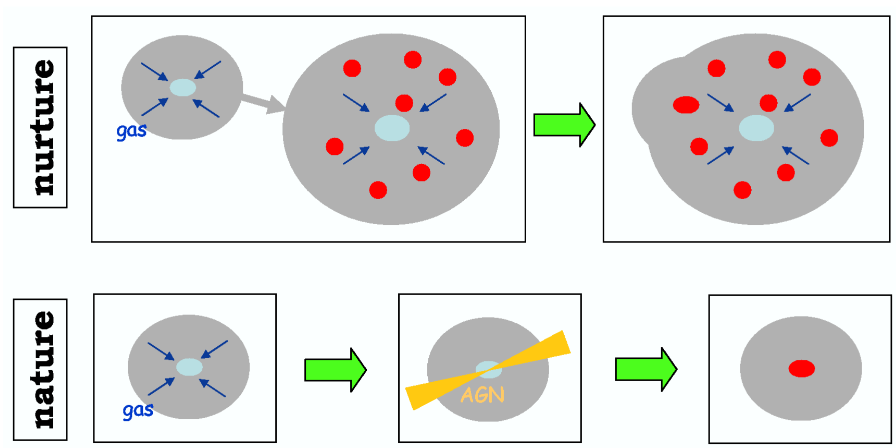

Figure 1. The origin of old, red galaxies can be phrased in "nurture" versus "nature" terms. Here, "nurture" is a catch-all phrase for the processes which lead to the cessation of star formation in a galaxy which becomes a satellite in a more massive halo. "Nature" refers to the various processes that have been proposed to suppress star formation in galaxies when they exceed a critical halo mass, such as AGN feedback and shock heating.

2. The Stellar Age of Massive Galaxies

A long-standing prediction of hierarchical models is that massive galaxies in low mass halos have very different formation histories than massive galaxies in high mass halos. Cluster galaxies form early and their evolution is effectively frozen shortly after they become part of a dynamically relaxed massive halo: their velocities are too high to permit mergers, and various processes rob them of their ability to form new stars. By contrast, massive galaxies in the field are expected to grow substantially at late times through mergers and possibly star formation (e.g., Kauffmann 1996, de Lucia et al. 2006).

We first turn to the star formation epoch of massive galaxies. The Kauffmann (1996) models, which did not include AGN feedback, predicted that the

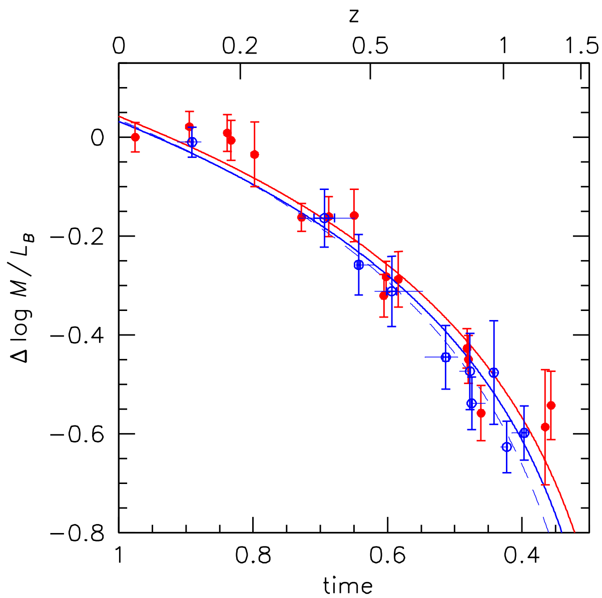

Figure 2. Evolution of the M/L_B ratio of early-type galaxies with stellar masses $> 10^{11}\, M_\odot$, in the field (blue) and in clusters (red), from van Dokkum & van der Marel (2007). The age difference between field and cluster galaxies implied by their luminosity evolution is small at $\sim 4\,\%$.

stars in field early-type galaxies[1] should be younger than those in cluster early-type galaxies by ~ 4 Gyr. Models that include AGN feedback (e.g., de Lucia et al. 2006) predict a much smaller age difference, of order ~ 0.7 Gyr.

Observational studies of early-type galaxies have provided conflicting evidence on the age difference between massive field- and cluster early-type galaxies. Studies of the local $\mathrm{Mg}_2 - \sigma$ relation and Fundamental Plane (FP) find very small age differences between field and cluster galaxies (e.g., Bernardi et al. 2006). However, Thomas et al. (2005) and Clemens et al. (2006) find age differences of $1.5 - 2$ Gyr from fitting absorption line strengths of nearby galaxies with complex models that include age, metallicity, α-enhancement, and (in the case of Clemens et al.) carbon enhancement as free parameters. Studies at higher redshift are also ambiguous: Treu et al. (2005), van der Wel et al. (2005), and Rusin & Kochanek (2005) find very small age differences from measurements of M/L ratios, but di Serego Alighieri et al. (2006) find age differences of $3.5 - 4$ Gyr from very similar data.

In order to resolve these conflicting results, and to provide a robust measurement of the stellar age of massive galaxies, we have recently compiled FP measurements of cluster- and field galaxies at $0 < z < 1.3$ from the literature, and placed them on a consistent photometric and dynamical system (van Dokkum & van der Marel 2007). The results are shown in Fig. 2: the M/L ratios of massive field and cluster galaxies evolve in very similar fashion, with

[1] In the local Universe, the most massive galaxies are early-type galaxies – although this may not hold at higher redshift.

little or no systematic offset. Their age difference is 0.4 ± 0.2 Gyr, inconsistent with nurture-only models and in good agreement with the de Lucia et al. (2006) AGN feedback model.

3. Dry Mergers

The ability of current semi-analytical models to reproduce the stellar ages and colors of massive elliptical galaxies at $0 < z < 1$ is a major achievement, but it is somewhat tangential to one of their central tenets: the prediction that these objects were assembled relatively recently through mergers. In clusters mergers should be rare, as the relative velocities of galaxies are too high. However, in the general field mergers should continue to the present day. Specifically, the de Lucia et al. (2006) model predicts that massive ellipticals typically assemble 50 % of their final mass at $z < 0.8$, and 20 % at $z < 0.4$. It is fairly clear, both observationally and theoretically, that these recent mergers must have been mostly "dry". The star formation induced by gas-rich mergers would dramatically change the colors and M/L ratios of massive elliptical galaxies, inconsistent with observations. Similarly, semi-analytical models predict that the most recent mergers of massive galaxies were mostly gas-poor (e.g., Khochfar & Burkert 2003; Kang, van den Bosch, & Pasquali 2007).

Observationally, there is good evidence that dry mergers frequently occur in $z \sim 1$ clusters, before they are fully virialized (van Dokkum et al. 1999, Tran et al. 2005, Mei et al. 2006). However, the importance of dry merging in the general field is still somewhat of an open question. Summing up current thinking: (1) there is no doubt that dry mergers occur; (2) they likely affected a large fraction of the elliptical galaxy population; but (3) they may have had only a limited effect on the evolution of the luminosity function of red galaxies.

Starting with (1), the recognition of dry mergers goes back to the Hubble atlas and Arp's catalog (see, e.g., Arp 169 – 172) — although back then mergers were not classified by their aridity. Combes et al. (1995) studied the stellar dynamics of E-E pairs and illustrated some of the features that occur in mergers of hot stellar systems. An example of a dry merger at $z = 0.1$ is shown in Fig. 3: the ground-based image shows the tidal features, the ACS image shows the early-type morphologies of the interacting pair, and the spectrum demonstrates that the red colors stem from old stars, not from a dust-enshrouded star burst.

The difficulty in assessing (2), i.e., how many elliptical galaxies experienced dry mergers, is that they progress very rapidly and leave little evidence. Tidal tails disperse quickly due to the high velocity dispersions of the progenitors, and the blue, high surface brightness star forming regions that often grace gas-rich mergers are absent. Detecting tidal features requires very deep imaging over large areas. When those depths are reached, red, smooth tidal features turn out to be very common: in a sample of 86 bulge-dominated red galaxies in the NDWF and MUSYC surveys 71 % show evidence for tidal interactions (van Dokkum 2005; see also Schweizer & Seitzer 1992). In one-third of the tidally distorted galaxies the merger is still in progress, and the properties of the merging galaxies could be measured. The median luminosity ratio of these tidally interacting pairs is about 1 : 3, and the median color difference is only -0.02 in $B - R$. Taken together, these results indicate that the majority of

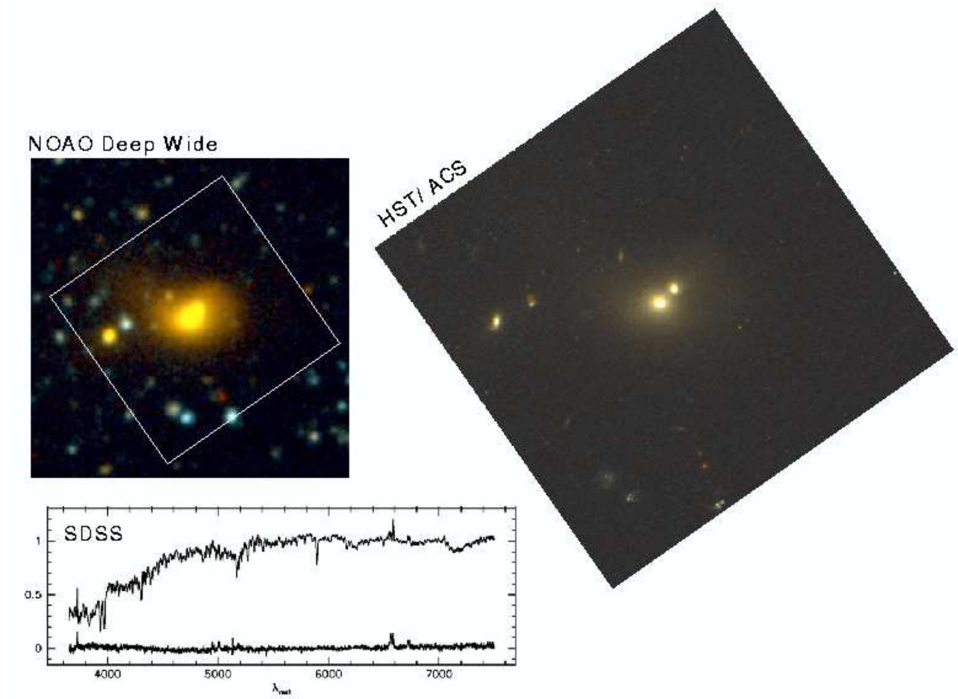

Figure 3. Example of a dry merger in the NOAO Deep Wide-Field Survey, from van Dokkum (2005). The deep ground-based data were used to identify the merging pair by its tidal features (which have a surface brightness of $R \approx 27$). The spectrum shows that the galaxy light is dominated by old stars (note the LINER features), and the ACS image shows that, in this case, the merging galaxies have early-type morphologies.

elliptical galaxies experienced a merger in its past, that the progenitors were already mostly "red and dead", and that these were not minor accretion events.

Determining (3), the dry merger rate, is perhaps the most important question, but it also is the most uncertain. From the 19 merging pairs in van Dokkum (2005) it was estimated that dry mergers lead to a mass-accretion rate for galaxies on the red sequence of $0.09 \pm 0.04\,\mathrm{Gyr}^{-1}$, that is, a doubling in mass every 8 Gyr. The uncertainty on this number is large, and mainly driven by the timescale that needs to be assumed in the calculation. Bell et al. (2006) also use morphological criteria to identify dry mergers (in the HST/ACS GEMS field), and estimate that early-type galaxies have undergone between 0.5 and 2 major dry mergers since $z \sim 0.7$. Red pair statistics will provide additional constraints on the dry merger rate. The first study was done by Masjedi et al. (2006a), who determined that the merger rate of Luminous Red Galaxies (LRGs) in SDSS is very low. However, this first analysis only considered mergers of LRGs *with each other*, and as these objects have $L \sim 4L_*$ they are typically the central galaxies of groups. Including less luminous neighbors, Masjedi et al. (2006b) derive an accretion rate of $\sim 0.025\,\mathrm{Gyr}^{-1}$, in better agreement with van Dokkum (2005), Bell et al. (2006), and theoretical models. We note that accretion rates of $2.5 - 10\,\%$ per Gyr do not imply a large effect on the luminosity function of red galaxies. Therefore, recent claims that the high-mass end of the mass function of red galaxies shows only modest evolution with redshift (Brown et al. 2007; Scarlata et al. 2007) may be entirely consistent with the quoted studies.

4. The Color-Density Relation at $z \sim 1$

The color-density relation might be expected to break down at some early epoch. Studies that access the star formation epoch of cluster galaxies may find that red galaxies are rare in dense environments, and see a rather flat (or possibly even inverted) color-density relation. The technical challenges are formidable, as large volumes need to be probed with good redshift information and a careful handling of systematics.

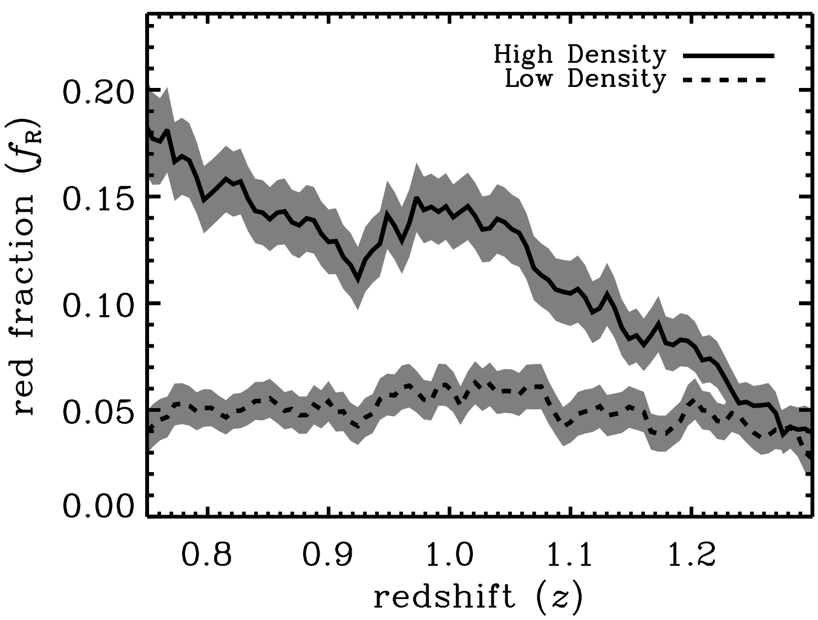

Figure 4. The evolution of the contribution of red galaxies to the total galaxy population, for two different density bins (from Cooper et al. 2007). The red galaxy fraction decreases strongly with redshift in high density regions, suggesting that the color-density relation disappears by $z \sim 1.3$.

Two groups have recently presented measurements of the color-density relation out to $z \sim 1.3$, based on very large spectroscopic surveys. Cucciati et al. (2006) use an I-selected sample of 6582 galaxies from the VIMOS-VLT Deep Survey (VVDS) to determine the evolution of the color-density relation. They find that the red fraction increases with density at redshifts up to $z \sim 0.9$, but then turns over so that it is independent of density at $z \sim 1.3$. Similarly, Cooper et al. find that the red galaxy fraction is about the same in low- and high-density regions at $z \sim 1.3$, from a sample of 19464 $R-$selected galaxies obtained in the context of the Keck DEEP2 survey (see Fig. 4). This "turnover" redshift seems rather low, in particular in light of the existence of clusters with well-defined red sequences at $z \sim 1.3$. Both studies applied careful corrections for selection

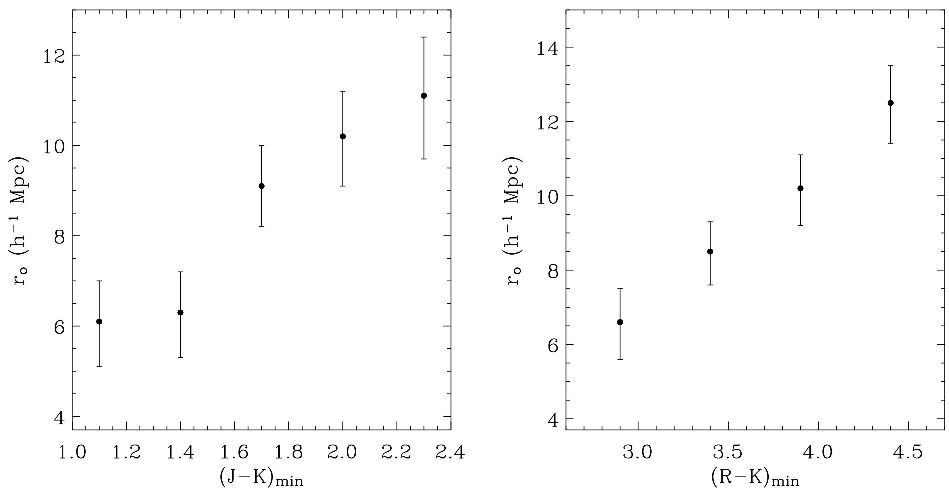

Figure 5. The relation between correlation length and color, for galaxies at $2 < z < 3.5$ in the MUSYC survey (Quadri et al. 2007). There is a clear correlation, implying that the color-density relation was already in place at this epoch.

effects (a necessity, as both surveys are highly incomplete at $z > 1$), and the fact that they are in agreement with each other obviously bolsters the confidence in their findings. Further refinement of these intriguing results may have to await surveys which probe the redshift range $1 < z < 2$ with the same robustness as DEEP2 and VVDS have surveyed the Universe out to $z \sim 1$.

5. Evidence for a Color-Density Relation at $z \sim 2.5$

It is not yet possible to study the color-density relation at $z > 2$ with the same tools as has been done at $0 < z < 1.3$. Nevertheless, some progress has been made, by employing different techniques. Steidel et al. (2005) compared the masses and ages of galaxies in an overdensity at $z = 2.3$ to those of other galaxies at the same redshift, with the aid of Spitzer photometry. Galaxies in the overdensity have masses and ages which are a factor of ~ 2 larger than those of identically-selected galaxies outside the structure, implying that galaxies already "know" of their large-scale environment at this early epoch. Continuing on this theme, Kodama et al. (2007) recently identified a red sequence in overdensities centered on four radio galaxies at $2 < z < 3$.

Another approach is to determine the relative clustering strength of red and blue galaxies. Daddi et al. (2003) found that red galaxies (selected by their $J - K$ color; Franx et al. 2003) in HDF-South cluster more strongly than blue galaxies. A similarly high clustering length was derived by Grazian et al. (2006) in the CDF-South. These initial results were confirmed by Quadri et al. (2007), who for the first time probed sufficiently large areas to study the clustering of the dark matter halos of red galaxies. As shown in Fig. 5, there is a clear relation between color and correlation length at $z \sim 2.5$, suggesting that the color-density relation was already in place at this redshift.

6. Summary

Although environment clearly plays an important role in galaxy formation and evolution, the similarity of massive galaxies in clusters and in the general field demonstrates that other processes are also at work. There is good evidence that galaxies in clusters and in the field experienced significant "dry" merging, but the merger rates need to be determined better. Studies beyond $z = 1$ offer a somewhat confused picture, with the color-density relation seemingly absent at $z \sim 1.3$ and seemingly in place at $z \sim 2.5$. Ongoing near-IR and Spitzer imaging surveys should greatly enhance the statistics, and allow direct comparisons of high redshift galaxies in a wide range of environments.

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