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The morphology-density relation: a constant of nature

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Abstract. The Sloan Digital Sky Survey (SDSS) and photometric/spectroscopic surveys of two $z \sim 0.8$ massive clusters of galaxies and the Chandra Deep Field-South (CDFS) are used to construct volume-limited, stellar mass-selected samples of galaxies at redshifts $0 < z < 1$ in a large range of environments. Morphologies are determined visually and with an automated method, using the Sérsic parameter n and a measure of the residual from the Sérsic model fits, called "bumpiness", to distinguish different morphologies. The agreement between the visual and automated methods is excellent. The fraction of E+S0 galaxies with masses larger than $\sim 0.5\ M^*$ is $40 - 50\%$ in the field, and $> 80\%$ in the clusters, without significant changes with redshift. Therefore, we find that the morphology-density relation (MDR) for galaxies more massive than $\sim 0.5\ M^*$ has remained constant since at least $z \sim 0.8$. This implies that galaxy evolution (in terms of mass, star formation, color, morphology, etc.) must happen such that the MDR does not change.

Keywords. galaxies: clusters: general, galaxies: elliptical and lenticular, cD, galaxies: evolution, galaxies: formation, galaxies: fundamental parameters

1. Introduction

The MDR (Dressler 1980), i.e., the observation that dense environments contain a higher fraction of early-type galaxies than low-density environments, provides a clue about the formation and evolution of galaxies, and suggests that environment plays an important role in shaping the galaxy population. The interpretation of the MDR, however, is not straightforward because of additional correlations between morphology, galaxy mass, color, star formation history, and metallicity; all quantities that depend on environment (e.g., Kauffmann *et al.* 2003; Baldry *et al.* 2006).

The evolution of the MDR can tell us when the relationship between galaxy properties and environment was established, and, even more importantly, how that happened. Significant evolution of the early-type galaxy fraction has been found between $z \sim 1$ and the present (Dressler *et al.* 1997, Smith *et al.* 2005, Postman *et al.* 2005), with lower early-type fractions in the past. These studies are based on luminosity-selected samples, taking luminosity-evolution with redshift into account. It is assumed that the evolution is the same for all galaxies, which might not be the case. In addition, luminosity is very sensitive to bursts of star formation that are likely far more prevalent at $z \sim 1$ than in the local universe. Therefore, it is worthwhile to adopt an alternative selection method, and stellar mass is a quantity that changes less rapidly than luminosity, such that it might be a more suitable tracer of the $z \sim 1$ progenitors of local galaxies.

In this paper we will describe the results of two studies by Holden *et al.* (2007) and van der Wel *et al.* (2007) in which we measure the evolution of the early-type galaxy fraction for mass-selected galaxies in a large range of environments, from the dense cluster cores to the field.

2. Sample Selection

2.1. *The Cluster Samples*

The low-redshift baseline is provided by the Coma cluster. In Holden *et al.* (2007) we describe the photometric and spectroscopic sample selection. Model magnitudes from SDSS imaging of the Coma sample from Dressler (1980) are determined by fitting Sérsic profiles in the g band. Subsequently, the $g-r$ model colors are determined by fitting the r-band image, using the Sérsic model parameters (except for surface brightness) derived in the g band. Morphologies are taken from Dressler (1980). The environment is quantified by calculating the local surface density of galaxies within $3000\,\mathrm{km\,s^{-1}}$ in radial velocity based on the distance to the 7th nearest neighbor (see, e.g., Postman *et al.* 2005).

The high-redshift cluster sample contains galaxies in the clusters MS1054 and RXJ0152, both at $z = 0.83$. For the spectroscopic samples (see Holden *et al.* 2007) colors are measured within the effective radius as determined by fitting a Sérsic profile to the available ACS imaging in the F775W filter (see also, Blakeslee *et al.* 2006). For the morphological classifications we refer to Postman *et al.* (2005). Local surface densities are determined using the same method as for the Coma sample.

For both samples, stellar masses are estimated with the relation between the $g-r$ color and g-band mass-to-light ratio (M/L). Extensive tests by various authors have shown that the relation between optical color and (dynamical) M/L does not change by more than ~ 0.1 dex for early-type galaxies (van der Wel *et al.* 2006; Holden *et al.* 2007) and maybe 0.2 dex for late-type galaxies (Kassin *et al.* 2007). The $z \sim 0.8$ cluster sample is complete down to a stellar mass of $4 \times 10^{10}\ M_{\odot}$ (for a Salpeter IMF).

2.2. *The Field Samples*

In order to enlarge the dynamic range in environment, we construct complementary samples of field galaxies in the same redshift range as the cluster samples described in the previous section (see van der Wel *et al.* 2007 for details). A low-redshift sample ($0.020 < z < 0.045$) is extracted from the SDSS, for which we measure colors, magnitudes and stellar masses using the same methods as for the Coma cluster discussed above.

Morphologies are determined with an automated method designed by Blakeslee *et al.* (2006). The two parameters that determine the morphology of a galaxy are the Sérsic parameter n and the 'bumpiness' parameter B. The latter is the *rms* of the residual from the Sérsic profile fit within two effective radii. For 200 galaxies in our SDSS sample we also determine visual morphologies, simply distinguishing between early- and late-type galaxies, where we consider E and S0 galaxies as early types. The correspondence between the visual and automated classifications is excellent (see Fig. 1), at least as long as we are concerned with only two morphological types. Distinguishing between, for example, Es and S0s is considerably harder.

A field galaxy sample at redshifts $0.6 < z < 1.0$ is constructed from the extensive spectroscopic campaigns conducted in the CDFS, which also has deep HST/ACS imaging (Giavalisco *et al.* 2004), with which we determine magnitudes, colors and morphologies. The applied techniques are generally the same as for the distant cluster samples described in the previous section. The main difference is that we use our automated classification method in order to be consistent with the low-redshift SDSS sample. However, as we show in Fig. 1, there is no systematic difference between the automated and visual morphologies, neither at low redshift, nor at high redshift. The distant field sample is complete down to $4 \times 10^{10}\ M_{\odot}$. Not all galaxies have spectroscopic redshifts: 30% have photometric redshifts only, but those are included to ensure completeness. For both the

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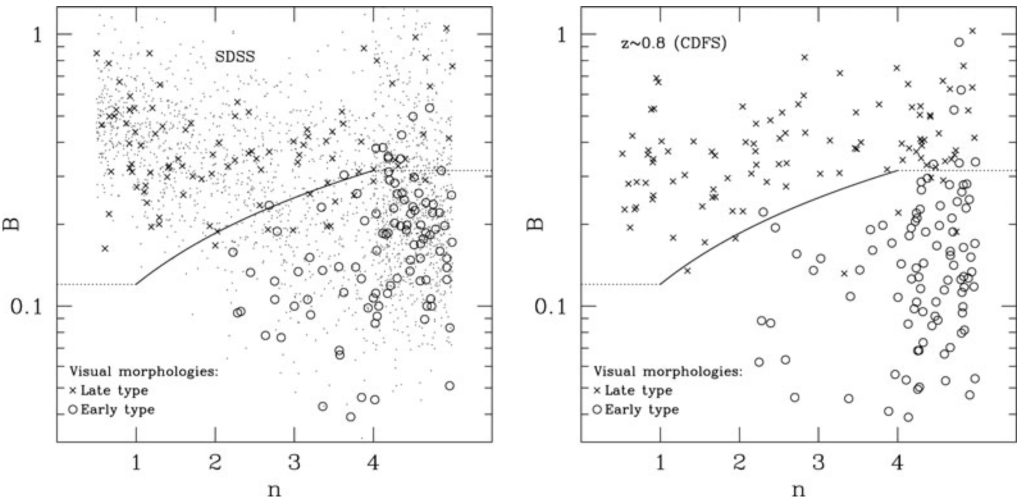

Figure 1. Illustration of our automated classification method used for the field galaxy samples (a: the low-z SDSS sample; b: the high-z CDFS sample). The Sérsic parameter n and the 'bumpiness' parameter B effectively distinguish between early- and late-type galaxies, as demonstrated by the excellent agreement with visual classifications: visually classified early types (Es and S0s) are indicated by circles, and late types by crosses.

local and distant field samples the environment is quantified by measuring the distance to the 7th nearest neighbor within $1000\,\mathrm{km\,s^{-1}}$ in radial velocity.

3. The Evolution of the MDR

In Fig. 2 we show the MDR at low and high redshift. As can be seen, the early-type fraction does not change significantly in either low- or high-density environments. In other words, for galaxies more massive than $4 \times 10^{10}\ M_{\odot}$ the MDR has been in place and has not evolved in shape or normalization since, at least, $z \sim 0.8$. The early-type fraction in the field is $40 - 50\%$, and the cluster early-type fraction is $> 80\%$, both at $z \sim 0.8$ and the present.

One may ask how this result should be interpreted in the context of the well-established picture that the early-type fraction declines significantly with redshift for luminosity-selected samples (e.g., Postman *et al.* 2005). Holden *et al.* (2007) demonstrate that the evolution seen in luminosity-selected samples is driven by blue, low-mass galaxies that satisfy the selection criteria because of their low M/L, i.e., because of their star formation activity and/or young stellar populations. Consequently, evolution in the morphological mix of galaxies may take place below our mass threshold. This threshold is not particularly low, in fact, it is only half of the mass of a typical (L^*) field galaxy. Therefore, the morphological mix of galaxies with typical luminosities and masses has not changed over the past 7 Gyrs, whereas at lower masses considerable evolution may take place, as evidenced by the large numbers of bright, but low-mass galaxies in the distant clusters.

Another question that may be raised is whether an unchanging morphological mix is consistent with the abundant evidence for significant changes in the galaxy population between $z = 1$ and the present. For example, the mass density in red galaxies has at least doubled since $z \sim 1$ (e.g., Bell *et al.* 2004), and the cosmic star formation activity has decimated since $z \sim 1$ (see, e.g., Madau *et al.* 1996; Le Floc'h *et al.* 2005). In fact, in our field sample we see that the typical star formation rate is considerably lower at $z \sim 0.03$ than at $z \sim 0.8$. Also, despite the small sample sizes, the mass densities of

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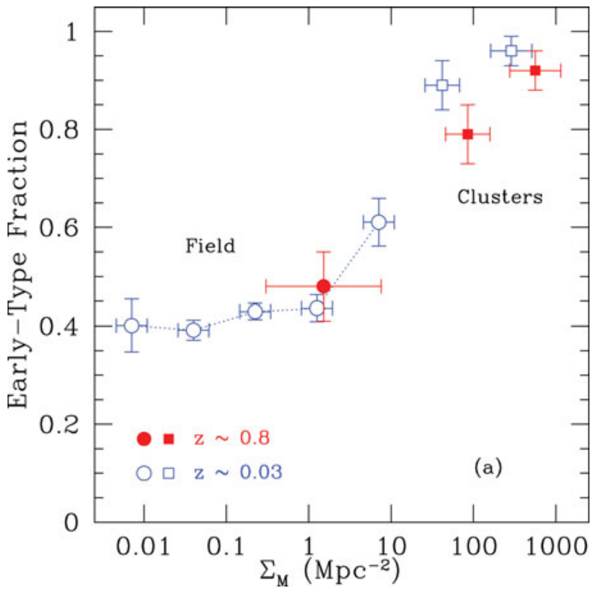

Figure 2. The MDR for galaxies with masses $M > 4 \times 10^{10}$ $M_{\odot}$ at the present day (open, blue symbols) compared with the MDR at $z \sim 0.8$ (filled, red symbols). The cluster data points (the squares) are from Holden *et al.* (2007); the field data points (the circles) are from van der Wel *et al.* (2007). There is no significant evolution in the early-type fraction in any environment, such that the MDR has been in place and has not evolved since, at least, $z = 0.8$.

our sample are consistent with an increase in the mass density of red galaxies between $z \sim 0.8$ and $z \sim 0.03$. The build-up of the galaxy population happens such that the relative number of early-type galaxies does not significantly change. For galaxies with a given mass, the probability that it has an early-type morphology is determined by the environment. Since that probability does not depend on cosmic time, as far as we have probed, we can say that the MDR is a constant of nature, and therefore plays an essential role in understanding the formation and evolution of galaxies.

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