TESTING THE HYPOTHESIS OF THE MORPHOLOGICAL TRANSFORMATION FROM FIELD SPIRAL TO CLUSTER S0

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ABSTRACT

Hubble Space Telescope observations of distant clusters have suggested a steep increase in the proportion of S0 galaxies between the distant clusters and clusters at the present-day. It has been proposed that this increase results from the transformation of the morphologies of accreted field galaxies from spirals to S0s. We have simulated the evolution of the morphological mix in clusters based on a simple model in order to test this morphological transformation hypothesis. In order to reproduce the apparently rapid increase in the ratio of S0 galaxies to ellipticals in the clusters, our model requires that: (1) galaxy accretion rate has to be high (more than half of the present-day cluster population must have been accreted since \( z \approx 0.5 \)), and (2) most of the accreted spirals, with morphological types as late as Scdm, must have transformed to S0’s. Although the latter requirement may be difficult to meet, it is possible that such bulge-weak spirals have already been ‘pre-processed’ into the bulge-strong galaxies prior to entering the cluster core and are eventually transformed into S0’s in the cluster environment.

On the basis of the evolution of the general morphological mix in clusters our model suggests that the process responsible for the morphological transformation takes a relatively long time (\( \sim 2 \) Gyr) after the galaxy has entered the cluster environment.

Subject headings: galaxies: elliptical and lenticular — galaxies: formation — galaxies: evolution

1. INTRODUCTION

The morphologies of galaxies remain one of the key observational characteristics used to classify and differentiate classes of galaxies. It is known from observations of the local Universe that galaxy morphology depends on environment, with the galaxy population within clusters dominated by early-types and spirals being found predominately in lower-density environments. Even within the clusters, the morphological mix changes with local galaxy density (and hence with cluster-centric distance) – producing a morphology-density relation – as shown by Dressler (1980, D80). Moreover, similar segregation behaviour has been seen in Hubble Space Telescope (HST) imaging of nine clusters at higher redshifts, \( z \approx 0.37–0.56 \) by Dressler et al. (1997, D97). These results confirm galaxy morphologies as one of the most sensitive tracers of environmental influences currently known.

One of the most interesting results to come out of the morphological studies of distant clusters has been the claim by Dressler et al. (1997) that the S0-to-elliptical (S0/E) ratio is a strongly decreasing function of redshift: by a factor of \( \sim 5 \) between \( z \sim 0 \) and 0.5 (although see Andreon 1998). This contrasts with the increasing number of blue, spiral galaxies seen in these regions at higher redshifts, which is the origin of the Butcher-Oemler effect (Butcher & Oemler 1984; Dressler et al. 1994; Couch et al. 1994; 1998; D97). D97 therefore proposed that most of the cluster S0’s are formed relatively recently by the morphological transformation of spirals (see also Poggianti et al. 1999). These spiral galaxies are continuously supplied by accretion from the surrounding field in the course of the assembly of the cluster. Couch et al. (1998, C98) and Pasano et al. (2000) have added estimates of the S0/E ratios for three clusters at \( z = 0.31 \) and nine clusters at \( 0.09 < z < 0.26 \), respectively, to bridge the gap in the D97 analysis between \( z = 0.37 \) and the present-day. These studies confirm the trend of a decreasing cluster S0 population from \( z = 0 \) out to \( z \gtrsim 0.5 \). Theoretical mechanisms for transforming the morphologies of bulge-strong spirals to S0 galaxies have been proposed by Moore et al. (1996; 1999a) based on high resolution N-body simulations, while gas dynamical processes, e.g. ram-pressure stripping (Abadi, Moore & Bower 1999), will also aid in truncating the star formation and hence fading the disk component of any spiral galaxy within the cluster environment.

The luminous galaxy populations in rich clusters at \( z \sim 0 \) are dominated by passive galaxies with early-type morphologies and apparently old stellar populations, as shown by their tight color-magnitude relation (e.g. Bower, Lucey & Ellis 1992). The transformation of star-forming spiral galaxy to passive cluster member must occur, as the blue, spiral galaxies we see in clusters at \( z \sim 0.5 \) cannot escape and hence their descendents have to reside in these regions at the present-day (Bower, Kodama & Terlevich 1998; Smail et al. 1998; van Dokkum et al. 1998). Following the work by Poggianti et al. (1998) and Smail et al. (1998) on the relationship between the blue galaxies in distant clusters and nearby cluster S0’s, Kodama & Bower (2000) quantified the analysis by sketching the flow of galaxies across the color-magnitude diagram down to the present-day, taking into account the galaxy accretion from the surrounding fields.

Motivated by this success in connecting the photometric evolution of the galaxy populations in distant clusters to the present-day counterparts within the framework of the assembly of rich clusters, we now try to seek to explain the evolution of the morphological mix in clusters, and especially the decline in the S0 population, in the context of a model for the growth of clusters and the evolution of their galaxy populations.

Since the proportion of spiral to ellipticals galaxies in the field is much higher than that in clusters at any time from \( z \sim 0.5 \) down to the present-day (e.g. Driver et al. 1998; van den Bergh et al. 2000), continuous accretion of galaxies from the field should be an effective process in changing the mor-
phological mix in clusters. If field spiral galaxies are turned into S0’s upon accretion to clusters, the galaxy accretion process effectively increases the fraction of S0 galaxies with time, and might explain the rapid increase of S0/E ratio presented in D97. The aim of this Letter is to test this hypothesis quantitatively and thereby constrain both the galaxy accretion rate and the timescale of the morphological transformation. Unless otherwise stated, we use $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$ and $q_0 = 0.1$.

2. MODELLING THE EVOLUTION OF THE MORPHOLOGICAL MIX IN CLUSTERS

To model the evolution of the morphological mix within the distant clusters we start from the distribution of morphologies in the faint field population based on the classifications from the Medium Deep Survey (MDS, Griffiths et al. 1994) using HST: E, 10%; S0, 10%; Sab, 25%; Scdm, 30%; and Irr, 25% (as used by Smail et al. 1997b). The magnitude limit for this sample is $I = 22$ and at this depth the median redshift of the population is $z \sim 0.5$ (Lilly et al. 1995). This morphological mix is consistent with the smaller sample of van den Bergh et al. (2000) in the Hubble Deep Field with spectroscopic redshifts which place them at $z \sim 0.25–0.6$. This then provides us with a morphological distribution for the field galaxies which are accreted onto clusters at $z < 0.5$.

We then add this population onto the morphologically-classified galaxy sample seen within clusters at $z \sim 0.5$: E, 42%; S0, 16%; Sab, 28%; Scdm, 7%; and Irr/compact/unclassified (these numbers are the average for the four most distant clusters in the Smail et al. (1997b) sample used by D97). We further assume that the bulge-strong galaxies observed in the clusters are in the process of morphological transformation into S0’s and we ignore merging of galaxies, since it is unlikely to be important for typical galaxies in these rich cluster environments, at $z \lesssim 0.5$, where the relative velocities are high ($\gtrsim 1000$ km s$^{-1}$).

Using these assumptions we devise a series of models for the evolution of the morphological mix in clusters from $z \sim 0.5$ to $z = 0$ (see below for details). We compare the resulting evolution of S0/E and Sab/S0 ratios with the observations from D97, C98 and D80. As we show below, these comparisons constrain both how large a fraction of the cluster population must be accreted since $z \sim 0.5$ and how long the morphological transformation takes. There are three key parameters in the model: (1) the total galaxy accretion rate onto the cluster; (2) the range of spiral types (e.g. Sab, Scdm) which transform into cluster S0’s, and (3) the timescale of this morphological transformation. We note that the accretion rate and morphological range have almost the same effect on the morphological evolution in the clusters, since both determine how many of the accreted field galaxies are turned into S0’s. In contrast the transformation timescale controls how long the accreted field spirals are classified as having ‘spiral’ morphology. The parameters for the models we consider are summarised in Table 1.

The cumulative galaxy accretion rate onto a cluster, $A_{\text{cum}}(t)$, is normalised to unity at $z = 0$ (equivalent to $t = t_{\text{univ}}$, the age of the present-day Universe – 16.6 Gyr in our cosmology) as:

$$A_{\text{cum}}(t_{\text{univ}}) = \int_0^{t_{\text{univ}}} A(t) dt = 1,$$  \hfill (1)

where $A(t)$ is the normalised accretion rate at a cosmic time $t$. To quantify the amount of recent accretion we define $A_{\text{recent}}(t)$, the integrated accretion rate from time $t$ (or redshift $z$) to the present-day ($t = t_{\text{univ}}$, or $z = 0$):

$$A_{\text{recent}}(t) = A_{\text{cum}}(t_{\text{univ}}) - A_{\text{cum}}(t).$$  \hfill (2)

The actual form for the accretion rate is taken from the Extended Press-Schechter theory (Bower 1991), assuming a power spectrum with $n = -1.5$. Based upon the weak lensing estimates of the masses of the clusters used in D97’s analysis (Smail et al. 1997a) we adopt a mass for the present-day cluster of 100 $M_\odot$, or $\sim 10^{15} M_\odot$. Since the galaxy accretion history is strongly dependent on the threshold mass for the substructure within the clusters (Bower 1991), we take the fiducial threshold mass of 10, 30 and 50 $M_\odot$ for the low, high and super-high accretion rate models, respectively.

| Models | $A_{\text{recent}}$ | Morphological Transformation | $\tau_{\text{trans}}$ (Gyr) |
|--------|---------------------|-----------------------------|-----------------------------|
| (a) hi-all-2 | high | Sab+Scdm $\rightarrow$ S0 | 2 |
| (b) lo-all-2 | low | Sab+Scdm $\rightarrow$ S0 | 3 |
| (c) hi-early-2 | high | Sab+Scdm $\rightarrow$ S0 | 1 |
| (d) hi-all-3 | high | Sab+Scdm $\rightarrow$ S0 | 3 |
| (e) hi-all-1 | super-high | Sab+Scdm $\rightarrow$ S0 | 1 |

Note — 1 The three different accretion rates in the models correspond to $(A_{\text{recent}}(z = 0.5), A_{\text{recent}}(z = 0.3)) = (0.35, 0.2)$ [low], $(0.5, 0.3)$ [high] and $(0.7, 0.4)$ [super-high].

For a particular accretion history, the evolution of the morphological mix (fraction of E, S0 and Sab galaxies) in clusters is calculated as follows:

$$f_{E}(t) = \frac{1}{A_{\text{cum}}(t)} \left(A_{\text{cum}}(t) - A_{\text{cum}}(t_{\text{trans}})\right) \times f_{\text{E}}^{\text{field}},$$  \hfill (3)

$$f_{S0}(t) = \frac{1}{A_{\text{cum}}(t)} \left(A_{\text{cum}}(t) - A_{\text{cum}}(t_{\text{trans}})\right) \times f_{\text{S0}}^{\text{field}},$$  \hfill (4)

$$f_{\text{Sab}}(t) = \frac{1}{A_{\text{cum}}(t)} \left(A_{\text{cum}}(t) - A_{\text{cum}}(t_{\text{trans}})\right) \times f_{\text{Sab}}^{\text{field}},$$  \hfill (5)

where $t_{\text{trans}}$ is the cosmic time at $z = 0.54$ (9.8 Gyr in our cosmology), the epoch at which we normalise the fraction of ellipticals and S0’s ($f_{E}(t_{\text{trans}}) = 0.42$ and $f_{S0}(t_{\text{trans}}) = 0.16$, D97). $\tau_{\text{trans}}$ is the timescale for the morphological transformation from a spiral to S0 after accretion, and $f_{\text{field}}^{\text{Sp} \rightarrow S0}$ is the fraction of field galaxies that are eventually turned into cluster S0’s, and is taken as:

$$f_{\text{field}}^{\text{Sp} \rightarrow S0} = \left\{\begin{array}{ll}
 f_{\text{Sp} \rightarrow S0}^{\text{field}} & \text{Model (c)}, \\
 0.25 & \text{Model (c)},
 \end{array}\right.$$  \hfill (6)

3. COMPARISON WITH OBSERVATIONS

In Figs. 1 and 2, we reproduced the observed S0/E and Sab/S0 ratios, respectively, from D97, C98 and D80. The D97 and C98 samples are cut at an absolute magnitude of $M_V = -20$ (we note that the magnitude limit quoted in D97 for their analysis is incorrect and actually corresponds to $M_V = -20$), in order to match the nearby cluster sample from D80 which is limited at an absolute magnitude equivalent to $M_V \sim -20.4$ (D97). We would have preferred to use an even brighter magnitude cut for the distant cluster samples (D97, C98) as galaxies can
faded substantially (~1 mag) after they cease star formation (see Kodama & Bower 2000). However, we adopted a limit of $M_V = -20$ to assure the largest galaxy sample and hence the best statistics for the distant clusters. We have checked that the morphological mix in the distant clusters hardly changes if we use, for example, $M_V = -21$. In addition, because of the morphology–density relation (D97), it is important to use equivalent areas in the nearby and distant clusters when comparing the galaxy populations. The morphological mix in the high redshift clusters in D97 and C98 is calculated within the HST fields, which roughly correspond to the inner 130 arcsec or 1.0 Mpc ($\sim 0.5$) diameter regions. For the nearby sample from D80 we use the same physical radius to define the morphological sample. Here we use the ten high concentration clusters from D80 as in D97, and their averaged morphological ratios are plotted by squares with error-bars indicating one sigma scatter between these clusters.

We also plot in Figs. 1 and 2 the model S0/E and Sab/S0 ratios as a function of redshift calculated from our model. Fig. 1 shows that the evolution of the S0/E ratio depends largely on the recent accretion rate (compare Models (a), (b) and (f)) and/or what proportion of the accreted spiral population is turned into S0’s (Models (a) and (c)), and that it is relatively insensitive to the transformation timescale $\tau_{\text{trans}}$ (Models (a), (d) and (e)). To match the strong evolution seen in the observations we must have both a high accretion rate, $\gtrsim 50\%$ of the cluster population added since $z \sim 0.5$, and also transform the majority of the accreted spirals into S0s (not only bulge-strong Sab galaxies, but also bulge-weak Scdm’s). We discuss the possibilities for transforming bulge-weak spirals into S0’s in §4. Based upon Fig. 1 we conclude that Models (a), (d), (e) and (f) are preferred.

A further constraint on the models comes from the spiral fraction (Fig. 2). As our model assumes that most spiral galaxies observed in the cluster cores are undergoing a morphological transformation into S0’s, the fraction of spiral galaxies in clusters can be used to estimate the timescale of this process. However, the spiral fraction also depends on the accretion rate and/or the proportion of the total spiral population which can transform into S0’s. As the S0 fraction depends upon the same parameters, we can reduce this dependence by normalising the Sab fraction using the S0 fraction. The Sab/S0 ratio thus depends primarily on the morphological transformation timescale and so can be used to constrain this timescale. We show in Fig. 2 the predicted Sab/S0 ratios for our models and compare these to the observations. To illustrate the dependence on the transformation timescale we show three models: (d), (a) and (e) for which $\tau_{\text{trans}} = 3, 2, 1$ Gyr respectively. As Fig. 2 shows, if $\tau_{\text{trans}}$ is too short (1 Gyr in Model (e)), the model struggles to retain enough accreted spirals as cluster spirals before they are transformed into S0’s. On the other hand, Model (d) ($\tau_{\text{trans}} = 3$ Gyr) over-produces the proportion of cluster spirals compared to the observations. Equally, adopting a very strong accretion rate model, Model (f), which is consistent with the S0/E ratio evolution (Fig. 1), and $\tau_{\text{trans}}$ of 1 Gyr tends to underestimate the Sab/S0 ratios (Fig. 2). Therefore our model suggests that the timescale for the morphological transformation should be in the range $\tau_{\text{trans}} \sim 1–3$ Gyr.

Note that we have included field Scdm’s into the cluster Sab category in the models, except for Model (c) (Eqs. (5) and (6)), since it is possible that the accreting Scdm’s are transformed into S0’s either prior to or immediately after their entry into the cluster cores (§4). If we did not take into account this ‘pre-transformation’ or ‘immediate transformation’ from bulge-weak spirals to bulge-strong ones, the Sab/S0 ratios in the models would go down by ~50 %. In this case, only Model (d) would reproduce the observed trend, suggesting $\tau_{\text{trans}} \sim 3$ Gyr.

The relatively long timescale we require for the morphological transformation is consistent with other recent results. Based upon the paucity of post-starburst signatures in the spectra of the luminous S0 population in distant clusters and the prevalence of red, passive galaxies with late-type morphologies, Poggianti et al. (1999) concluded that the morphological transformation of S0’s had to occur on a longer timescale than the stel-
lar evolution timescale of any A stars formed in the most recent star formation event in these galaxies (either while they were in the field, or any activity which was induced on entering the cluster). Comparisons between the properties of the luminous S0 and elliptical galaxies in distant clusters have been used to place limits on the relative evolution of the two populations: work on three clusters at $z = 0.31$ – using spectral (Jones, Small & Couch 2000) and photometric (Couch et al. in preparation) analysis concluded that the S0 and elliptical populations are remarkably homogeneous, and similar conclusions were reached using precise photometric analysis of the colors of S0/ellipticals in the cluster cores at $z = 0.18$ (Smail et al. 2000), those at $z = 0.33$ (van Dokkum et al. 1998) and those at $z \sim 0.5$ (Ellis et al. 1997). All of these studies suggest that the luminous S0 galaxies in the cluster cores ceased their star formation at least 2 Gyr prior to the observed epoch (but see the discussion in Smail et al. 2000 for less luminous S0’s). Observations of the evolution of the color distribution of cluster galaxies (Kodama & Bower 2000) and the radial gradients in star formation, measured using [OIII], (Balogh, Navarro & Morris 2000) both suggest that the star formation in a galaxy is terminated only relatively slowly after it has been accreted by a cluster, $\sim 1$ Gyr. Taken together these two timescales would indicate that an accreted star-forming spiral galaxy transforms into a passive S0 within $\sim 2$ Gyr of entering the cluster environment. Our analysis confirms this suggestions and in addition places an upper limit on the transformation timescale of $< 3$ Gyr.

4. DISCUSSION AND CONCLUSIONS

Our model is able to reproduce the broad properties of the morphological evolution of cluster populations across $\sim 7$ Gyr from $z \sim 0.5$ to the present-day. The observed evolution of the S0/E ratio requires high rates of accretion onto the clusters and also that a significant fraction of all accreted spiral galaxies, both bulge-strong Sab and bulge-weak Scdm, are transformed into S0’s. This is a concern as there is no obvious and effective mechanism for transforming an Scdm into an S0. The bulges of late-type spirals are simply not luminous enough to form the dominant bulges of S0 galaxies as a result of stopping the star formation in the disk or even by 'harassment' in the cluster environment (Moore et al. 1996). One possibility would be that the accreted field populations are not the same as 'pure' field population we assumed from the MDS. They may be 'pre-processed' in group or sub-cluster units. or intrinsically biased towards earlier types. Most of the bulge-weak Scdm’s may have already turned to bulge-strong galaxies by merging or through bar-formation due to strong galaxy harassment/interaction, before entering the clusters. This is likely, given that the vicinity of a rich cluster, where accreting spirals are located, originates from a high density region at the early Universe (e.g. Moore et al. 1999b). Therefore, the morphological mix in the near cluster field tends to be skewed towards earlier Hubble types than that in the pure field through galaxy-galaxy interactions in a dense region (e.g. Moore et al. 1999a; 1999b; Baugh, Cole & Frenk 1996).

Alternatively, in a high density Universe with $\Omega_o = 1$ ($q_0 = 0.5$), for example (Bower 1991), the accretion rate is higher than in our models. $\Delta_{\text{acc}}(z = 0.5) \gg 0.1$. And if this is really the case, the large S0/E ratio at $z \sim 0$ can be reached without the need to transform Scdm’s into S0’s. Furthermore, the S0/Sab ratio would also be consistent even with $t_{\text{trans}} = 1$ Gyr. However, recent observations suggest slower cluster evolution than expected in an $\Omega_o = 1$ cosmology, with little evolution seen in X-ray luminosity function of clusters out to $z = 0.3$ (Ebeling et al. 1997) and beyond (Fairley et al. 2000), indicating the recent accretion rate cannot be that high.

In summary, we have simulated the evolution of the morphological mix in clusters using a simple model in which the accreted field spirals are transformed into S0’s in the cluster environment. In order to reproduce the rapid increase in the S0/E ratio between distant clusters and their present-day counterparts, it is found that at least half of the present-day cluster population must have accreted since $z \sim 0.5$. In addition, not only the bulge-strong field spirals, but also the relatively bulge-weak field spirals must have eventually transformed into cluster S0’s. Finally, morphological transformation from spirals to S0’s upon entry to clusters is found to be a relatively slow process ($\sim 2$ Gyr) in order to keep their morphology as spirals for enough time to explain the fraction of cluster spirals.

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