Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY LETTERS

Mon. Not. R. Astron. Soc. **401,** L39–L43 (2010) doi:10.1111/j.1745-3933.2009.00782.x

Quantitative measure of evolution of bright cluster galaxies at moderate redshifts

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Accepted 2009 October 31. Received 2009 October 31; in original form 2009 September 27

ABSTRACT

Using archival data from the *Hubble Space Telescope*, we study the quantitative morphological evolution of spectroscopically confirmed bright galaxies in the core regions of nine clusters ranging in redshift from $z = 0.31$ to 0.84. We use morphological parameters derived from two-dimensional bulge–disc decomposition to study the evolution. We find an increase in the mean bulge-to-total luminosity ratio as the Universe evolves. We also find a corresponding increase in the fraction of early-type galaxies and in the mean Sérsic index. We discuss these results and their implications to physical mechanisms for evolution of galaxy morphology.

Key words: galaxies: evolution – galaxies: formation – galaxies: fundamental parameters – galaxies: photometry.

1 INTRODUCTION

Clusters serve as laboratories for investigating the dependence of galaxy morphology on the density of the environment. Dressler (1980) found that the fraction of early-type galaxies increases with local density of galaxies. He also found that around 80 per cent of galaxies in nearby clusters are of the early type. In recent years, deep, high-resolution imaging by the *Hubble Space Telescope (HST)* has helped to extend the study of galaxy morphology as a function of the environment to $z \sim 1$. The observed fraction of different morphological types can be explained in terms of both ‘nature’ and ‘nurture’ scenarios. The former argues that a galaxy’s morphological type is determined by initial conditions at formation (e.g. Eggen, Lynden-Bell & Sandage 1962), while the latter depends on the influence of the environment and of secular evolution for determining the final morphological type (e.g. Toomre 1977). Numerical simulations play an important role in investigating the relative importance of the two scenarios under different physical conditions.

Following Dressler’s pioneering work, many observational studies have been done to measure and understand the morphology–density relation (MDR), and the dependence of morphological type on distance of the galaxy from the cluster centre (Dressler et al. 1997; Goto et al. 2003; Treu et al. 2003; Postman et al. 2005; Smith et al. 2005; Capak et al. 2007; Holden et al. 2007). Smith et al. (2005) found that the early-type fraction is constant in low-density environments over the last 10 Gyr, but there is significant evolution in this fraction in higher density regions. According to Smith et al. (2005), this suggests that most of the ellipticals in clusters formed at high redshift, and the increase in the fraction of early-type galaxies, is because of the physical processes in dense regions which transform disc galaxies with ongoing star formation to early types. Dissipationless merging of cluster galaxies may also be responsible for this increase.

There is increasing evidence to show that massive ellipticals formed by dissipationless (dry) merger of two or more systems. Such ellipticals must have formed at later times than their low-luminosity counterparts (de Lucia et al. 2006). van Dokkum (2005) analysed tidal debris of elliptical galaxies and concluded that ∼70 per cent of the bulge-dominated galaxies have experienced a merger. The analysis of nearby bulge-dominated galaxies has shown that the gas-to-stellar mass ratio is very small and these mergers are mostly ‘dry’. Using a semi-analytic model for galaxy formation, Naab, Khochfar & Burkert (2006) found that both the photometric and kinematic properties of massive elliptical galaxies are in agreement with the scenario where massive elliptical galaxies are produced by mergers of lower mass ellipticals. They suggested that the merger of two spiral galaxies alone cannot reproduce the observed properties, and that the large remnant mass ($>6 \times 10^{11}\,M_{\odot}$) implies that they must have undergone elliptical–elliptical mergers. They found that this process is independent of the environment and redshift, which means that dry mergers can occur at low redshift as well. By analysing spirals from cluster and group environments at intermediate redshift ($z \sim 0.5$), Moran et al. (2007) found that the Tully–Fisher relation shows larger scatter for cluster spirals than for those in the field. They also found that the central surface

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mass density of spirals in clusters is small beyond the cluster virial radius, and argued that these observations provide evidence for merger/harassment.

Mergers are not common in clusters, as the velocity dispersion of virialized clusters is large. So, if ellipticals in clusters have formed by mergers, that most likely happened during the early stage of cluster collapse (Roos & Aarseth 1982). There is some observational evidence to support this idea. van Dokkum et al. (1999) showed that there is a large fraction of ongoing mergers in a cluster at $z = 0.83$. The observation of the unvirialized cluster RX J0848+4453 at $z = 1.27$ revealed many ongoing dissipationless mergers of galaxies (van Dokkum et al. 2001). These observations go against the view of monolithic collapse where all the ellipticals formed at the same time, at a very high redshift.

In this Letter, we report on the evolution of galaxies in the core region of clusters, measured using bulge–disc decomposition. We show that in the case of brightest cluster galaxies, the fraction of galaxies with bulge-to-total luminosity ratio $(B/T) > 0.4$ and $n > 2.5$ evolved significantly over the redshift range 0.31 to 0.83. Throughout this Letter, we use the standard concordance cosmology with $\Omega_\Lambda = 0.73$, $\Omega_\mathrm{m} = 0.27$ and $H_0 = 71\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$.

2 CLUSTER SAMPLE AND DECOMPOSITION TECHNIQUE

We have exclusively used archival *HST* data in this work. All of the observations used by us were obtained with either the ACS or Wide Field Planetary Camera 2 (WFPC2) cameras on board the *HST*. We constructed our sample of clusters by an extensive literature survey of *HST* observations of moderate-redshift clusters. The clusters we study span the redshift range 0.31 to 0.837. The clusters were selected such that they each had at least 15 spectroscopically confirmed cluster members listed in the literature (Smail et al. 1997; Couch et al. 1998; Dressler et al. 1999; Williams et al. 1999; Halliday et al. 2004; Demarco et al. 2005). We restricted our study only to those clusters whose second brightest member galaxy has an absolute magnitude between −25 and −27 in rest-frame *B* band. Here, the magnitudes are corrected for the cosmological surface brightness dimming. This criterion allows us to restrict ourselves to clusters of roughly comparable luminosity. Further, we only included clusters with imaging data around the rest-frame *B* filter, i.e. in filters where the central wavelength of the filter corresponded to a rest-frame wavelength in the range 350 to 550 nm. This has the advantage that the *k*-correction for transformation from *R* or *I* filters in the observer frame, to the *B* filter in the rest frame, has only a weak dependence on galaxy spectral type in the redshift range $0.3 \lesssim z \lesssim 0.8$ (Böhm & Ziegler 2007). Incompleteness of the spectroscopy is a potential problem; since our data are drawn from a heterogeneous set of observations, it is not possible to correct for incompleteness in a completely consistent way. However, for the five clusters in our sample which are part of the European Southern Observatory Distant Clusters Survey, Halliday et al. (2004) have shown that incompleteness does not introduce a significant bias. The level of incompleteness is also relatively small because they (like us) restrict themselves to the brighter cluster members. Nine clusters satisfied our selection conditions at the time of commencing this study; the basic data for these clusters are given in Table 1.

The images we downloaded from the *HST* data archive were processed in a standard way using the On-the-Fly Reprocessing (OTFR) pipeline at STScI. The processed images were dark and bias-subtracted and flat-fielded by the OTFR pipeline. We combined them using the MULTIDRIZZLE package (Koekemoer et al. 2002) to flag and remove cosmic rays and to correct for geometric distortion and produced a single co-added image. For some clusters, multiple disjoint pointings have been used; in such cases, we obtained multiple multidrizzled images. The correlated pixel noise introduced by the drizzle process was corrected for using the prescription of Casertano et al. (2000).

We computed the centre of each cluster as the centroid of the brightest cluster galaxy. We then selected all galaxies with a spectroscopic redshift confirming their cluster membership and located within a 1 Mpc projected distance from the cluster centre. Our study is therefore restricted to galaxies lying (mostly) within the core region of the clusters. Note that for three clusters – AC 114, CL 0303+17 and 3C 295 – the *HST* imaging is not complete for the 1 Mpc projected distance.

Galaxies are known to undergo luminosity evolution, to account for which we adopted the following simple scheme: $M_V(z) = M_V(z = 0) - 0.8\, z$, where z is the redshift of the object and $M_V(z = 0) = -19.5$ (Postman et al. 2005). The magnitude cut-off in the observed *HST* filter was then calculated using

$$m_\mathrm{lim} = M_V(z) + DM - (M_V - M_{HST}) + k_{HST}, \quad (1)$$

where DM is the distance modulus, $M_V - M_{HST}$ is the rest-frame colour between V and the observed *HST* filter and k_{HST} is the k-correction in the observed *HST* filter. The k-correction for each cluster was computed using the elliptical SED provided by Poggianti (1997). All magnitudes are in the Vega system.

With all the above constraints, we obtained a sample of 379 galaxies in nine clusters. We used the GALFIT (Peng et al. 2002) program for 2D bulge–disc decomposition of the galaxy images. To fit the galaxies, we have developed an automated pipeline (Vikram V. et al., in preparation) which completely automates the fitting procedure and organizes the results into a data base, supplemented by a number of diagnostic plots to detect anomalies. The basic steps

Table 1. Summary data for sample clusters.

Cluster	RA	Dec.	z	Camera	Filter	m_lim	N_Tot	N_Fit	Reference
AC 114	22 58 48.4	−34 48 60	0.31	WFPC2	F702W	20.77	72	68	Couch et al. (1998)
CL 0303+17	03 06 15.9	+17 19 17	0.42	WFPC2	F702W	21.64	28	26	Smail et al. (1997)
3C 295	14 11 19.5	+52 12 21	0.46	WFPC2	F702W	21.93	37	32	Smail et al. (1997)
CL 1232−1250	12 32 30.3	−12 50 36	0.54	ACS	F814W	21.66	46	41	White et al. (2005)
CL 1054−1146	10 54 24.4	−11 46 19	0.697	ACS	F814W	22.44	30	25	White et al. (2005)
CL 1040−1155	10 40 40.3	−11 56 04	0.704	ACS	F814W	22.47	25	19	White et al. (2005)
CL 1054−1245	10 54 43.5	−12 45 51	0.75	ACS	F814W	22.68	29	28	White et al. (2005)
CL 1216−1201	12 16 45.3	−12 01 17	0.794	ACS	F814W	22.89	50	43	White et al. (2005)
RX J0152.7−1357	01 52 27.4	−13 55 01	0.837	ACS	F775W	23.50	62	55	Blakeslee et al. (2006)

m_lim : faint magnitude cut-off in the observed *HST* filter, N_Tot : total number of galaxies, N_Fit : number of galaxies with good fit.

in performing the 2D decomposition are as follows: (1) make a cut-out image for each galaxy, including neighbouring galaxies, (2) estimate starting values of fitting parameters using the parameters measured by SExtractor, (3) make masks to exclude stars, faint galaxies and other artefacts and (4) run galfit. Bright neighbouring galaxies were fitted simultaneously with the target galaxy. We modelled each galaxy as a linear sum of a Sérsic (for the bulge) and an exponential (for the disc) component. The centres, position angles, ellipticities and central surface brightnesses of bulge and disc were fitted simultaneously. The Sérsic index was left unconstrained. The estimation of galaxy parameters, particularly the Sérsic index, may be systematically affected if the sky or point spread function (PSF) are incorrectly estimated. To test for the effect of using an incorrect PSF, we ran the decomposition for each galaxy using two stellar PSFs, one constructed using the nearest star and the other using the second nearest star and compared the fitted values of B/T and n for every galaxy. To test for incorrect sky, we ran the decomposition in two modes: one in which the sky was left as a free parameter and the other in which it was fixed to the local sky value as determined by SExtractor. In both tests, ~80 per cent of galaxies showed random changes in the extracted parameters at <10 per cent level, with no obvious systematics. Our simple tests are consistent with the extensive simulations of Häussler et al. (2007) which showed that galfit estimates parameters accurately for *HST* data, even at relatively shallow depths. As an additional precaution, we examined the fit results, by eye, for every galaxy. The fit diagnostic plots were used to evaluate the quality of the fit. We used the reduced χ^2 given by galfit to identify galaxies with large residuals. A large residual in the central part of the galaxy may be caused by improper estimation of the PSF. Also, simultaneous fitting with neighbour galaxies needs special care as the number of free parameters is significantly larger. For galaxies that show a large residual, we took these caveats into consideration and refit the galaxies until the residual became small. We then assigned a quality factor for each galaxy based on the magnitude of the residual and the deviation of fitted position angle from the galaxy position angle estimated by eye. If a fit was below a threshold quality, we excluded that galaxy from further analysis. We found that most of the galaxies that failed the quality check have either peculiar morphology or strong spiral arms. We successfully fit 337 out of 379 galaxies in our sample. Unless otherwise stated, all further discussion in this Letter only applies to these 337 galaxies. The cluster-wise breakup of galaxies with a good fit is given in Table 1.

3 RESULTS

3.1 Evolution of mean bulge-to-total luminosity ratio ($\langle B/T\rangle$) and Sérsic index n

In Table 2, we list mean and median values of a few parameters of interest for all the nine clusters. Note that the B/T is computed using the parameters of the best-fitting model. We find that the $\langle B/T\rangle$ of cluster galaxies in the central 1 Mpc of the clusters changes from $0.59^{+0.03}_{-0.02}$ at redshift $z = 0.31$ to 0.48 ± 0.03 at $z = 0.837$ (Fig. 1). In this and subsequent figures, errors were measured using the bootstrap resampling method (Efron & Tibishirani 1993). The increase in $\langle B/T\rangle$ ratio has been found qualitatively (i.e. using visual morphological classification) by previous studies (Dressler et al. 1997; Fasano et al. 2000; Smith et al. 2005). The present work obtains the result quantitatively using bulge–disc decomposition. It must be noted that, if our sample is somewhat biased towards luminous red galaxies at //high z, and if such galaxies are early type

Table 2. Mean and median parameters obtained through bulge–disc decomposition.

Cluster	$\langle B/T\rangle$	$\langle n\rangle$	ñ	f_b
AC 114	$0.59^{+0.03}_{-0.02}$	$4.13^{+0.43}_{-0.39}$	$3.47^{+0.27}_{-0.30}$	$0.55^{+0.03}_{-0.04}$
CL 0303	$0.52^{+0.05}_{-0.05}$	$4.24^{+1.02}_{-0.79}$	$3.31^{+0.20}_{-0.83}$	$0.46^{+0.05}_{-0.07}$
3C 295	$0.52^{+0.04}_{-0.05}$	$3.47^{+0.59}_{-0.56}$	$3.17^{+0.72}_{-0.78}$	$0.43^{+0.03}_{-0.04}$
CL 1232−1250	$0.48^{+0.04}_{-0.04}$	$4.15^{+0.56}_{-0.52}$	$3.30^{+0.41}_{-0.52}$	$0.47^{+0.04}_{-0.05}$
CL 1054−1146	$0.45^{+0.05}_{-0.05}$	$3.60^{+0.76}_{-0.65}$	$2.41^{+1.02}_{-0.43}$	$0.26^{+0.05}_{-0.06}$
CL 1040−1155	$0.42^{+0.08}_{-0.07}$	$3.50^{+0.68}_{-0.68}$	$3.25^{+0.71}_{-0.56}$	$0.28^{+0.08}_{-0.08}$
CL 1054−1245	$0.47^{+0.05}_{-0.05}$	$2.80^{+0.38}_{-0.41}$	$2.55^{+0.56}_{-0.55}$	$0.37^{+0.05}_{-0.06}$
CL 1216−1201	$0.48^{+0.03}_{-0.04}$	$3.25^{+0.54}_{-0.44}$	$2.57^{+0.40}_{-0.51}$	$0.32^{+0.04}_{-0.04}$
RX J0152.7−1357	$0.48^{+0.03}_{-0.03}$	$2.74^{+0.28}_{-0.30}$	$2.49^{+0.43}_{-0.28}$	$0.40^{+0.02}_{-0.02}$

$\langle B/T\rangle$: mean value of B/T, $\langle n\rangle$: mean value of the Sérsic index, ñ : median value of the Sérsic index, f_b : fraction of bulge-like galaxies (see text for definition).

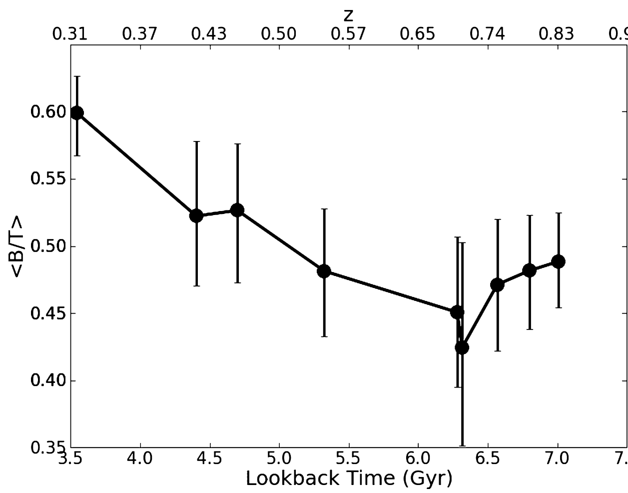

Figure 1. Evolution of mean value of the B/T.

even at those redshifts, our estimated $\langle B/T\rangle$ value represents an upper limit at $z \sim 0.8$. In addition, incompleteness will also tend to make our estimate of $\langle B/T\rangle$ too high because at fainter magnitudes we would preferentially miss low B/T late-type galaxies (Desai et al. 2007). This leads to our estimated $\langle B/T\rangle$ to be the upper limit for these clusters. So the selection bias, if any, will lead to an apparent weaker evolution. So, our estimation of evolution of $\langle B/T\rangle$ may be an underestimate.

We also find that the mean value of the Sérsic index decreases with lookback time over this redshift range. The value changes from $4.13^{+0.43}_{-0.39}$ to $2.74^{+0.28}_{-0.30}$ from $z = 0.31$ to 0.84. Fig. 2 shows the evolution of the Sérsic index against lookback time.

3.2 Evolution of bulge-like galaxy fraction

Since the $\langle B/T\rangle$ decreases significantly with lookback time, one expects to see a simultaneous decrease in the fraction of early-type galaxies with a bulge-like morphology. We classify a galaxy as bulge-like if its $B/T \geq 0.4$ and $n > 2.5$. The second condition is required to exclude galaxies with a very strong disc which can, on occasion, be incorrectly modelled as a bulge with $n \sim 1$ (an exponential), with a correspondingly high B/T luminosity ratio. With this definition, we are able to compute a bulge-like galaxy fraction for each cluster. In Fig. 3, we plot this fraction against

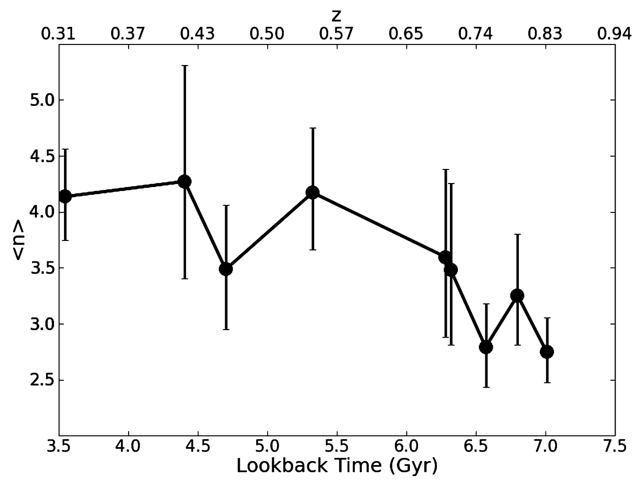

Figure 2. Evolution of mean value of the Sérsic index.

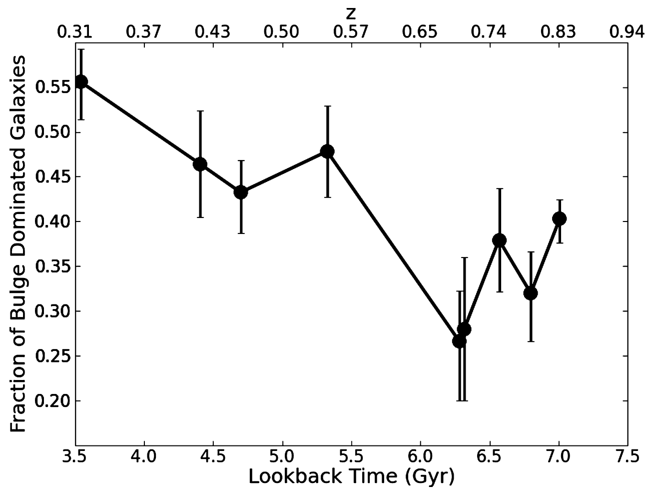

Figure 3. Evolution of fraction of bulge-dominated galaxies.

lookback time. Note that the fraction is normalized by the total number of galaxies in the cluster, not the number of galaxies with a successful fit. The galaxies that are poorly fit are dominated by galaxies of irregular morphology. We see a near monotonic decrease with lookback time in the bulge-dominated fraction of galaxies. We find that 40±2 per cent of galaxies at redshift $z = 0.837$ are bulge-like. This increases to 55^{+3}_{-4} per cent within ~3.5 Gyr.

3.3 Discussion

In the last decade, several studies have reported evolution of the morphological content of galaxy clusters by a visual study of galaxy morphology (Smail et al. 1997; Couch et al. 1998; Fasano et al. 2000; Desai et al. 2007). Other studies focused on the evolution of the MDR, where morphology changes were studied as a function of redshift and galaxy density (Dressler et al. 1997; Treu et al. 2003; Postman et al. 2005; Smith et al. 2005).

In this work, we have taken the first approach; however, we have used *quantitative* measures of galaxy morphology rather than a qualitative morphological classification by eye. We decompose the galaxy light into bulge and disc components and study the evolution of morphology of galaxies in clusters. We find that the bulge component of the *bright* galaxies in clusters is, on average, becoming stronger as the Universe evolves. The fraction of bulge-like galaxies, defined as having $B/T > 0.4$ and $n > 2.5$, also increases from 40 to 55 per cent. There is also a significant increase in the mean value of the Sérsic index as the Universe ages.

Our results on the evolution of morphological fraction are consistent with previous work on the subject (Dressler et al. 1997; Postman et al. 2005; Smith et al. 2005). However, Desai et al. (2007), using ACS observations of galaxy clusters with $0.5 < z < 0.8$, found no evolution of morphological fraction. At first glance, this seems to contradict our results. However, it must be noted that in our study, we are only including bright, spectroscopically confirmed cluster galaxies. If fainter galaxies are included, as was done in the sample of Desai et al. (2007), the ~10 per cent change we see in the morphological fraction may easily be washed out. This explanation also agrees with the results of Holden et al. (2007) who showed that there is evolution in the early-type fraction with redshift if a luminosity-limited sample is used.

Postman et al. (2005), Desai et al. (2007) and Poggianti et al. (2009) found that the E+S0 fraction correlates with the velocity dispersion of the cluster. The fraction is large for clusters with high dispersion. This effect would be consistent with the evolution we see, provided velocity dispersion systematically decreases with redshift. We see no systematic dependence of velocity dispersion with redshift except that the two highest redshift clusters in our sample have high velocity dispersions ($>1000\,\mathrm{km\,s^{-1}}$). This high value, which implies higher $\langle B/T \rangle$, is consistent with the mild increase of $\langle B/T \rangle$ and the fraction of bulge-dominated galaxies for the two high-z clusters. But the dominating effect seems to be the morphological evolution.

The $\langle B/T \rangle$ of a cluster may increase either due to an increase in the strength of the bulge component of galaxies or by the fading of disc component. The increase in average bulge strength may be caused by merging which tends to produce an elliptical-like morphology (van Albada 1982; Barnes 1992; Hernquist 1992; Bournaud et al. 2005; Khochfar & Silk 2009). On the other hand, the fading of the disc could be a by-product of the morphological transformation of galaxies. In clusters, a variety of mechanisms such as galaxy harassment (Moore et al. 1996; Moore, Lake & Katz 1998; Moore et al. 1999), minor mergers and ram-pressure stripping (Gunn & Gott 1972; Abadi, Moore & Bower 1999) may contribute to the disc fading.

The increase in the mean Sérsic index $\langle n \rangle$ with cosmic time seems to indicate that mergers play a role (Scannapieco & Tissera 2003). Merger events are common at intermediate redshift (Dressler et al. 1994). The increase in the fraction of galaxies with high B/T and Sérsic index is possible if galaxies gradually evolve into a phase where the spheroidal component increasingly dominates. The end point of such evolution is an elliptical galaxy.

It has recently been suggested that the bright S0 population has likely formed through monolithic collapse or major mergers (Barway et al. 2007, 2009). Numerical simulations have also shown that dissipative merger of two unequal mass disc galaxies (Bekki 1998; Bekki 2005) can produce lenticulars. Recent observations of low-redshift clusters suggest that a majority of the infall population is merging or interacting (Moss 2006). Coupled with the constraints from Carlberg (1986), it is becoming increasingly clear that formation of spheroidal (mostly lenticular) galaxies through mergers is the dominant mechanism behind systematic changes in galaxy morphology.

It must be noted that the trends we see are weak and statistical in nature; they are only visible when averaged over a large number of galaxies in a large number of clusters over a wide range of redshift. The detailed physics operating in each cluster doubtlessly modifies the morphological evolution of galaxies in that cluster. Nevertheless, the fact that we see trends indicates that they are real and strong enough not to be drowned by the different physical conditions and processes operating in individual clusters. Using the large data base of bulge/disc decomposition results we have obtained, we are attempting to disentangle cluster-specific effects from cosmological ones.

ACKNOWLEDGMENTS

VV acknowledges financial support from the Council of Scientific and Industrial Research (CSIR). We thank the referee for insightful comments and suggestions that greatly improved this Letter.

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