Enhanced mergers of galaxies in low-redshift clusters

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ABSTRACT

An ensemble cluster has been formed from a data set comprising a complete magnitude-limited sample of 680 giant galaxies (M_B ≥ −19) in 8 low-redshift clusters, normalised by the velocity dispersions and virial radii for the early-type cluster populations. Distinct galaxy populations have been identified, including an infall population. A majority (50–70% or greater) of the infall population are found to be in interacting or merging systems characterised by slow gravitational encounters. The observed enhancement of galaxy–galaxy encounters in the infall population compared to the field can be explained by gravitational shocking. It is shown that disc galaxy mergers in the infall population integrated over the estimated lifetime of the cluster (∼ 10 Gyr) can readily account for the present cluster S0 population.

Key words: galaxies: clusters: general – galaxies: evolution – galaxies: interactions

1 INTRODUCTION

Although the transformation of luminous cluster disc galaxy populations from mainly spirals to predominantly S0s between intermediate redshifts (z ∼ 0.5) and the present is well established (e.g. Dressler 1980; Dressler et al. 1997), there is as yet no agreed mechanism for this transformation. One of the earliest explanations proposed was galaxy–galaxy interactions and mergers (e.g. Lavery & Henry 1988; Lavery, Pierce & McClure 1992). This explanation is attractive both on account of the observed abundance of interacting/merging systems in intermediate redshift clusters (e.g. Dressler et al. 1994a, 1994b) and because the Hubble sequence is readily explainable as a sequence of decreasing merger damage (Schweizer 2000). Nevertheless this explanation was resisted because it was considered that slow galaxy–galaxy interactions and mergers are likely to be rare in virialised clusters (e.g. Ostriker 1980; Makino & Hut 1997; Ghigna et al. 1998). Although many other explanations have been attempted, including ram-pressure stripping of the cold interstellar gas of spirals by the hot ionised intracluster medium (e.g. Quilis, Moore & Bower 2000), galaxy ‘harassment’, the impulsive heating of a galaxy disc by high-speed encounters (e.g. Moore et al. 1996, 1999), and ‘strangulation’, the stripping of an (hypothesised) hot halo gas from spirals (e.g. Larson et al. 1980; Bekki, Couch & Shioya 2002), these explanations are not without difficulties (for a recent discussion, see Mihos 2004). Alternatively, attempts have been made to remove the problem entirely from clusters by proposing preprocessing of disc galaxies to earlier type systems in groups in the field (e.g. Balogh et al. 2004). However, as remarked by Mihos (2004), neglect of slow encounters has been premature. Numerical simulations which track galaxy halos in a rich cluster in an Ω_m = 1 cosmology show that between z = 0.5 and z = 0, although no mergers occur in the central virialised region of the cluster, in the outskirts the merger rate is 5–9% (see Ghigna et al. 1998). Gnedin (2003) has similarly studied the interaction and merger rates in clusters under different cosmologies. Over the lifetime of a cluster, the distribution of encounter velocities shows a large tail, but a significant fraction of encounters, largely those in the cluster periphery or those occurring at higher redshift before the cluster has fully collapsed, have relatively low velocity. For example, for an Ω_m = 0.4 Ω_λ = 0.6 cosmology, some 42% of encounters have a velocity ≤ 550 km s^{-1}.

As Mihos (2004) has noted, galaxy clusters form not by accreting individual galaxies randomly from the field environment, but rather through the infall of less massive groups falling in along the filaments that make up the ‘cosmic web’. Such infalling groups provide sites with much lower velocity dispersions than that of the cluster, thus permitting strong, slow encounters more normally associated with the field. For low-redshift clusters, such infall continues at the present (e.g. Moss & Dickens 1977; Tully & Shaya 1984; Sodre et al. 1989; Colless & Dunn 1996; Biviano et al. 1997; Rines et al. 2003). Besides the theoretical considerations outlined above, there is also accumulating observational evidence of the potential importance of galaxy mergers for morphological transformation of cluster disc galaxies, both at low and intermediate-redshift (e.g. Dressler et al. 1997; Moss, Whittle & Pesce 1998; Moss & Whittle 2000, 2005; Koopmann & Kenney 2004; Sato & Martin 2006).

In the present paper the infall population of nearby clusters is studied using data from an extensive morphological
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and star formation survey of 8 low-redshift clusters (Moss & Whittle 2000, 2005). These data are used to construct an ensemble cluster from which general properties of all the clusters can be deduced. It is shown that a very high fraction ($\sim 50$–$70\%$) of the infall population are either interacting or possible mergers. This interaction/merger rate is too high to be accounted for simply on the basis of infalling groups typical of the field, but implies that the accretion process of the cluster enhances the galaxy–galaxy interaction/merger rate.

It is suggested that galaxy shocking (Struck 2005) can provide a mechanism to enhance the interaction/merger rate, and that galaxy–galaxy interactions and mergers can provide an explanation for the transformation of most luminous cluster spirals to S0s over the past $\sim 10$ Gyr.

The paper is organised as follows. In section 2, the survey data are summarised and construction of an ensemble cluster is discussed. In section 3, various sub-populations of the ensemble cluster are identified, including that of the infall population. Member galaxies of the infall population are considered in detail and an estimate of the interaction/merger rate for this population is given. Discussion is given in section 4. It is shown that there is an enhancement of galaxy mergers in the infall population in comparison to the field; an explanation (gravitational shocking) is proposed for this enhancement; and finally it is shown that it is entirely plausible that the majority of the current S0 cluster population have resulted from galaxy mergers in the past $\sim 10$ Gyr. Conclusions are given in section 5.

2 Ha SURVEY

2.1 Survey galaxy sample and detected emission

Using the 61/94-cm Burrell Schmidt telescope on Kitt Peak, an objective prism survey was undertaken of combined Hα + [NII] emission in CGCG galaxies (Zwicky et al. 1960–68) in the low-redshift clusters, Abell 262, 347, 400, 426, 569, 779, 1367 and 1656. The surveyed galaxies were all those whose centric (1.5$r_A < r < 2.6r_A$). The full survey sample (including separate components of double galaxy systems) comprises 843 galaxies. The sample is magnitude-limited; redshifts for the galaxies are 96% complete. Further details of the survey, including discussions of galaxy classification and survey completeness, can be found in previous papers (cf. Moss, Whittle & Irwin 1988; Moss & Whittle 1993; Moss, Whittle & Pesce 1998; Moss & Whittle 2000, 2005; hereafter, papers I–V respectively).

Emission was detected in 5% of early-type (E–S0/a) and 41% of late-type (Sa + later) galaxies respectively. The survey distinguished between compact and diffuse emission. The former has been identified as predominantly due to circumnuclear starburst emission, while the latter is characteristic of more normal disc star formation. The compact HII emission is associated with a bar in the galaxy (significance level 3.1σ); with a tidally-disturbed morphology (significance level 8.7σ); and with the presence of a nearby galaxy companion (significance level 3.1σ). It is found that compact emission, particularly that associated with a tidally-disturbed galaxy morphology, is enhanced in clusters as compared to the field (cf. papers IV and V).

2.2 Ensemble cluster

For the present study, data for the 8 clusters have been combined into a single ensemble cluster. This procedure necessarily erases structural details for the individual clusters. However, as will be shown, important properties of all the clusters can be found from the combined data which would otherwise not be revealed by data from a single cluster alone.

The sample galaxies were combined into an ensemble cluster as follows: velocities were normalised by the cluster velocity dispersion, $\sigma$, and scaled to the cluster mean, $\bar{v}$; radial distances from the cluster centres (Abell 1958) were normalised by the virial radius, $r_{\text{vir}}$.

As will be shown in what follows, the cluster late-type galaxy population (types Sa + later) has an infalling component with higher velocity dispersion than the early-type cluster galaxies, as well as a component whose velocity distribution is asymmetric with respect to the cluster mean. In contrast, the early-type cluster population has a Gaussian distribution expected for virially relaxed galaxies in the cluster. A recent study of 59 clusters in the ESO Nearby Abell Cluster Survey has also confirmed that deviations from a Gaussian velocity distribution for early-type galaxies in the ensemble of these clusters are very small (cf. Katgert, Biviano & Mazure 2004). Moreover the early-type galaxies are generally considered to be the oldest cluster population and therefore most likely to be in dynamical equilibrium with the cluster potential. For these reasons, cluster mean (heliocentric) velocities and velocities dispersions have been determined from the early-type galaxies alone. For each cluster, $\bar{v}, \sigma$ were determined using biweight estimators of central location and scale (cf. Beers, Flynn & Gebhardt 1990; Teague, Carter & Gray 1990). The initial galaxy sample was all E,S0,S0/a galaxies with $r \leq r_A$ and $|v - \bar{v}| \leq 4\sigma$, where initial values for $\bar{v}$ and $\sigma$ were taken from Struble & Rood (1991). Solutions for $\bar{v}, \sigma$ were determined using 3 iterations and are listed in Table 11.

Values of the virial radii for the individual clusters were estimated using the relation $r_{\text{vir}} \approx 3.5\sigma(1+z)^{-1.5}$ (see Lewis et al. 2002), where $r_{\text{vir}}$ is in Mpc for $\sigma$ in units of 1000 km s$^{-1}$. The derivation of this relation assumes spherical symmetry, and that the galaxy distribution follows the mass distribution for the cluster (see Girardi et al. 1998). The virial radii thus determined are listed in Table 11. Abell 569 is a double cluster (north and south sub-cluster centres (J2000): $7^h\,10^m\,6\, +50^d\,07'\,\text{and}\,7^h\,9^m\,1\,+48^d\,37'\,\text{respectively}$); the radial distance from the cluster centre for an individual galaxy was taken as its distance from the nearest sub-cluster centre.

Using the values of $\bar{v}, \sigma$ and $r_{\text{vir}}$ given in Table 11 the sample galaxies for the 8 clusters were combined into a single ensemble cluster sample. Of the 843 galaxies in the original sample, 39 were excluded which are components of double systems with an estimated magnitude fainter than the survey limit ($m_p = 15.7$); 90 foreground/background galaxies ($|v - \bar{v}| > 4\sigma$) were also excluded. Of the remaining 714
Table 1. Cluster virial radii

| Cluster | $\bar{v}$ (E–S0/a only) (km s$^{-1}$) | $\sigma$ (km s$^{-1}$) | $n$ (Mpc) | $r_{vir}$ (r$_A$) |
|---------|-------------------------------------|-----------------------|-----------|------------------|
| Abell 262 | 4812 | 537 | 38 | 1.83 | 0.86 |
| Abell 347 | 5582 | 550 | 14 | 1.87 | 0.87 |
| Abell 400 | 6771 | 392 | 10 | 1.32 | 0.62 |
| Abell 426 | 5161 | 1076 | 55 | 3.67 | 1.72 |
| Abell 569 | 5868 | 417 | 26 | 1.42 | 0.66 |
| Abell 779 | 6991 | 290 | 11 | 0.98 | 0.46 |
| Abell 1367 | 6542 | 762 | 62 | 2.58 | 1.21 |
| Abell 1656 | 6944 | 890 | 131 | 3.01 | 1.41 |

Figure 1. Normalised velocity distribution scaled to the cluster mean velocity, for E, S0, S0/a galaxies in the ensemble cluster ($r \leq r_{vir}$). The dotted line is a normalised Gaussian fit to the data ($|v - \bar{v}| \leq 3\sigma$) with mean of 0 and dispersion of 1.

3 GALAXY POPULATIONS

The distribution of normalised velocities scaled to the cluster mean, $(v - \bar{v})/\sigma$, for E,S0,S0/a galaxies in the ensemble cluster ($r \leq r_{vir}$) is shown in Figure 1. Also shown in the figure is a normalised Gaussian fit to the data ($|v - \bar{v}| \leq 3\sigma$) with mean of 0 and dispersion of 1. As is seen, the data are well fitted by a Gaussian (K–S test, significance level = 0.53), consistent with the early-type cluster galaxy population being virially relaxed.

In Figure 2 the same velocity distribution for cluster galaxies ($r \leq r_{vir}$) of types Sa + later is shown. This distribution shows some positive asymmetry with respect to the normalised Gaussian. In order to better understand this distribution, it is useful to consider sub-populations of the cluster galaxy sample.

In previous work it was shown that galaxies of types Sa + later with disturbed stellar populations are more frequently found in clusters as compared to the field; moreover, such disturbed galaxies with compact HII emission have few counterparts in the surrounding supercluster field, and substantially account for the observed enhancement of galaxies with compact emission in clusters (cf. Papers IV and V). Accordingly it is convenient to begin the analysis of cluster galaxy sub-populations by distinguishing between galaxies with disturbed and undisturbed morphologies respectively.

In section 3.1 below, it will be shown that the galaxies with a disturbed morphology, which are predominantly of types Sa + later, most likely comprise an infall population to the clusters. In contrast, galaxies of types Sa + later with an undisturbed morphology are expected to be more typical of the outer cluster regions or the field (cf. section 4.3.2). The observed asymmetry of the velocity distribution for Sa + later is due to HII emission-line galaxies (ELGs) with an undisturbed morphology, which are likely to be members of galaxy groups accreting onto the clusters (see section 5).

It is to be noted that those few ELGs with known AGN or LINER emission ($n = 10; \sim 10\%$ of ELGs) have been omitted from the analysis, since the main interest of the present study is in the effect of environment on galaxy star formation. In fact, inclusion of these galaxies in the ELG samples does not significantly change the results obtained below.

3.1 Cluster infall population

In Figure 3 (upper panel) the normalised velocity distribution of all galaxies with a disturbed morphology in the ensemble cluster ($r \leq r_{vir}$) is shown. Classification of galaxies as disturbed or undisturbed has been taken from Papers III–V. The mean and dispersion (biweight estimators) for the velocity distribution are $0.05 \pm 0.19$ and 1.42 respectively. The mean is in agreement with that for the early-type (E, S0, S0/a) galaxies; however the dispersion is significantly greater than that expected for a sub-sample of the virialised cluster population (F test, significance level = $5 \times 10^{-4}$). In fact, the dispersion ($\sigma_v = 1.42$, with 90% confidence limits, 1.17, 1.56 estimated from bootstrap resampling) is in good agreement with the expected value of $\sqrt{2}$ for an infall population.

In the lower panel of the figure is shown the correspond-
Figure 3. As Figure 1 for (upper panel) all galaxies with a disturbed morphology and (lower panel) for HII ELGs with a disturbed morphology. The hatched area of lower histogram shows the distribution of galaxies with compact emission.

Figure 4. Distribution of galaxy types for all disturbed galaxies and (shaded histogram) HII ELGs with a disturbed morphology.

Figure 5. Cumulative distributions with $r/v$ for galaxy types (excluding galaxies with a disturbed morphology) E,S0,S0/a (solid line, $n = 354$) and Sa + later (dashed line, $n = 216$) in the ensemble cluster. Also shown are the cumulative distributions for (upper panel) all galaxies with a disturbed morphology (dotted line, $n = 65$), and (lower panel) HII ELGs with a disturbed morphology (dotted line, $n = 29$). All samples exclude galaxies with $|v - v| > 4\sigma$.

Clustering velocity distribution for HII ELGs with a disturbed morphology. The ELGs classified as having compact emission are shown in the hatched histogram. The mean and dispersion for the full HII ELG sample are $0.14 \pm 0.35$ and $1.75$ (90% confidence limits: $1.38$, $1.93$). Again, the mean is in accord with the cluster mean; however the dispersion is significantly greater than that expected for a sub-sample of the virialised cluster population ($F$ test, significance level $= 2 \times 10^{-5}$), and even higher than for the sample of all disturbed galaxies.

The samples of all disturbed galaxies, and HII ELGs with a disturbed morphology are predominantly of types Sa + later (71% and 85% respectively, see Figure 4). The velocity distribution for disturbed galaxies, restricted to types Sa + later, is intermediate between those for the two other samples with mean and dispersion of $-0.01 \pm 0.25$ and $1.55$ respectively ($n = 39$).

In the upper and lower panels of Figure 5 are shown the cumulative spatial distributions with $r/v$ of the samples of all disturbed galaxies, and HII ELGs with a disturbed morphology respectively. In each case the sample is compared to the cumulative distributions for (undisturbed) galaxies of types E,S0,S0/a and Sa + later. It is seen that the sample of all disturbed galaxies has a more concentrated distribution than that for undisturbed galaxies of types Sa + later. Remarkably, the distribution of the sample of HII ELGs with disturbed morphology is similar to that of the early-type population ($K$-S test, significance level $= 0.38$) and more concentrated than the (undisturbed) Sa + later galaxies ($K$-S test, significance level $= 7 \times 10^{-3}$) despite the fact that this ELG sample is predominantly comprised of types Sa + later (see Figure 4).
The simplest explanation for the higher velocity dispersion observed for all disturbed galaxies is that the disturbed galaxies are an infall population whose velocities have not yet been virialised. In Figure 6 (lower panel) the distribution of disturbed galaxies in the $r-v$ plane is shown, as compared to the corresponding distribution for E,S0,S0/a galaxies (upper panel). In the figure, HII ELGs with a disturbed morphology are shown as stars in the lower panel. In both panels, the dashed curves are caustics which are a measure of the cluster gravitational potential (Diaferio 1999); they show the maximum line of sight velocity for a radial infall population, as a function of distance from the cluster centre. These caustics were calculated using a standard NFW mass density profile for the E,S0,S0/a population with an assumed value of the concentration parameter, $c = 5.56$ (see Navarro, Frenk & White 1997; Biviano & Girardi 2003).

For a virially-relaxed population it is expected that points in the figure will cluster towards the axis, $(v - \langle v \rangle)/\sigma_v = 0$; in contrast, for a radial infall population with a similar mass density profile the density of points in the figure is expected to increase towards the caustics, with a relative dearth of points near to this axis (see Kaiser 1987). Such contrasting distributions are evident between the E,S0,S0/a and disturbed galaxies in the upper and lower panels of the figure. While the E,S0,S0/a galaxies have a distribution characteristic of a virially-relaxed population, the distribution of disturbed galaxies, most especially of the disturbed HII ELGs, is more spread out towards the caustics, thus reinforcing the conclusion that the disturbed galaxies are a cluster infall population.

It has long been known that spiral galaxies in clusters generally have a higher velocity dispersion than the early-type cluster population (e.g. Moss & Dickens 1977; Sodrê et al. 1989). Subsequent work established that it was the emission-line galaxy population of clusters which has the higher velocity dispersion (Biviano et al. 1997). The present work refines these observational insights: the infall population of the cluster comprises galaxies with disturbed morphologies. The velocity dispersion for this population is higher than that for the cluster and in accord with the expected value for an infall population. A subset of this population (and a subset of the entire ELG population) are HII ELGs with disturbed morphologies. As will be discussed below (see section 4.3), these ELGs are likely to be in the final stages of first infall, with the highest velocity dispersion of any cluster galaxy sample.

### 3.2 Cluster halo population

In Figure 7 is shown the velocity distribution for galaxies of types Sa + later with an undisturbed morphology. This sample has been divided into two sub-samples, viz. (upper panel) non-ELGs and (lower panel) HII ELGs. The hatched area of lower histogram shows the distribution of galaxies with compact emission. The dashed line in the lower panel shows the normalised distribution for an homogeneously distributed field population.
striking difference between the velocity distributions for the two samples. The non-ELG population closely approximates a Gaussian, whereas the HII ELGs have an asymmetrical distribution. In this section the non-ELG population is discussed. Consideration of the HII ELGs is given in the next section (3.3).

The velocity distribution of the non-ELG population is well fitted by a normalised Gaussian (K–S test, significance level = 0.31) with a mean and dispersion (biweight estimators) of $-0.05 \pm 0.11$ and 1.05 respectively in good agreement with values for the E,S0,S0/a population.

The cumulative spatial distribution with $r_{\text{vir}}$ for this population is compared with that for the E,S0,S0/a population in Figure 9. As is seen, the distribution for the non-ELGs is less concentrated than the corresponding early-type galaxies (K–S test, significance level = $3 \times 10^{-12}$). The distribution of the the non-ELGs in the $r$–$v$ plane is shown in Figure 10 (upper panel). This distribution lacks any signature of an infall pattern in contrast to that for disturbed galaxies (cf. Figure 6).

The less concentrated spatial distribution of the undisturbed non-ELGs of types Sa + later compared to the early-type cluster population, and their similar Gaussian velocity distribution to the latter, suggest that these non-emission spirals predominantly form a cluster halo population which may be already partially or mainly virialised.
3.3 Outer cluster population: accretion of groups

In Figure 7 (lower panel) the velocity distribution is shown of HII ELGs of types Sa + later, with an undisturbed morphology. As is seen, the velocity distribution has a marked asymmetry with respect to a normalised Gaussian with mean and dispersion (0,1) equal to that for the early-type population (biweight estimator, \( \bar{v} = 0.60 \pm 0.14; K-S\) test for Gaussian fit, significance level = \( 3 \times 10^{-5} \)). The velocity dispersion for the HII ELGs (biweight estimator, \( \sigma = 1.04 \)) is in agreement with that for the early-type population.

The cumulative distribution of these ELGs with \( r_{\text{vir}} \) is shown in Figure 6. In contrast to the population of HII ELGs with disturbed morphology which follow the distribution of the early-type population (see above, section 3.1), the present ELGs have a less concentrated spatial distribution (K-S test, significance level = \( 1.6 \times 10^{-6} \)).

As noted above, the undisturbed population of Sa + later galaxies may be expected to be in the outer cluster regions or in the field. Can the observed asymmetry of the velocity distribution of the HII ELG subset of this population be explained by field galaxy contamination? In Figure 7 (lower panel) the dashed line shows the expected normalised velocity distribution for these ELGs, assuming they are distributed as a homogeneous field population. This distribution was obtained by assuming a Schechter luminosity function typical for field galaxies with Ho equivalent width, \( W_\lambda \geq 20\AA \) (\( M^* = -19.17, \alpha = -1.24 \), see Madgwick et al. 2002). Note that the form of the distribution is insensitive to the exact value of the faint-end slope, since galaxies at the survey limit have an absolute magnitude approximately equal to the Schechter characteristic magnitude at the cluster distance. The expected distribution for an homogeneous field population shows that a significant fraction of the actual population of ELGs is more clustered, and is likely to be associated with the outer cluster regions rather than with the field. It also shows that the asymmetry in the velocity distribution for these ELGs cannot be ascribed to contamination by field galaxies, since such contamination would lead to a negative asymmetry, rather than the positive one observed.

This conclusion is reinforced by consideration of the velocity distribution of HII ELGs with undisturbed morphology of types Sa + later which lie beyond one virial radius from the cluster centre in the supercluster field shown in Figure 11. As is seen, there is an absence of the asymmetry shown in the distribution of corresponding cluster galaxies, and which might be expected if this asymmetry was due to field galaxy contamination.

Assuming that a significant fraction of this ELG sample is associated with the outer regions of the clusters, and further assuming that individual galaxies have a randomly distributed isotropic accretion onto the clusters, the probability of obtaining the observed velocity distribution (i.e. 79% of galaxies with \( v > \bar{v}; n = 57 \)) is \( P \sim 5 \times 10^{-6} \). This asymmetry in the velocity distribution is not due to the effect of a few clusters in the sample. In Table 2 normalised mean velocities and values of \( N^+, N^- \) the numbers of galaxies with velocities greater or less than the cluster mean respectively, are listed for individual clusters. As is seen, in all 7 cases, \( N^+ > N^- \).

However the assumption that individual galaxies have a randomly distributed isotropic accretion onto the clusters may be questioned. Clusters of galaxies are expected to form at the intersections of filamentary structures, and we might accordingly suppose that accretion takes place preferentially along these filaments. Moreover galaxies are likely to accrete onto clusters in large agglomerations which have already condensed out of the general field. In which case, there may be a predominant bulk inflow associated with a cluster, or group of clusters. For the sample of 8 clusters which comprise the ensemble cluster, one cluster (Abell 779) has no galaxies in the present sample; two clusters (Abell 1367, 1656) form a double cluster with separation ~ 33 Mpc; and three further clusters (Abell 262, 347, 426) form a group of clusters with mean separation ~ 18 Mpc. Accordingly if there are predominant bulk inflows associated with the double cluster, the group of clusters and individually with the remaining clusters (Abell 400, 569), it is no longer so surprising that these may produce the type of asymmetrical velocity distribution found for the present galaxy sample.

Although further investigation is needed, it is provisionally concluded that the sample of HII ELGs with undisturbed morphology of types Sa and later are likely to comprise a population in process of accretion onto the cluster, but which have not yet undergone relaxation within the inner regions of the cluster (\( r < r_{\text{vir}} \)) where their bulk streaming velocities would be randomised (cf. section 3.1). This view is consistent with the lack of a high velocity dispersion for this sample (\( \sigma_v = 1.04 \)), their undisturbed morphology, their comparatively high, often disc-wide, star formation, and the lack of any infall signature in their \( r-v \) distribution (see lower panel of Figure 10).

3.4 Galaxy–galaxy interactions and mergers

In Paper IV, galaxies of types Sa + later were ranked according to the presence of an apparent nearby interacting companion (> 20% of the size of the galaxy, and within ~ 5 galaxy diameters). If velocities were available for both the galaxy and companion, and \( |\Delta v| > 1500 \) km s\(^{-1}\), the galaxies were no longer considered to have ‘real’ companions. (Ei-
Table 3. Galaxies with companions. All cluster galaxy populations are restricted to types Sa + later, and exclude galaxies with |v − v| > 4σ.

| Cluster population (r ≤ vir) | n   | With companions | With companions or 'peculiar' |
|-------------------------------|-----|-----------------|-----------------------------|
| Undisturbed galaxies          |     |                 |                             |
| All                           | 134 | 7.5%            | 12.7%                       |
| HII ELGs                      | 47  | 6.4%            | 17.0%                       |
| Disturbed galaxies            |     |                 |                             |
| All                           | 30  | 53.3%           | 73.3%                       |
| HII ELGs                      | 16  | 37.5%           | 75.0%                       |

other the projected companion is a chance superposition, or |Δv| is too large for a slow gravitational encounter.) Likely projected companions were also rejected if the probability of a chance superposition, P > 0.05, based on estimates of the local surface density. Remaining galaxies with ranks C, C: (see Paper IV) were considered to have ‘real’ companions. In Table 4 the percentages of galaxies of types Sa + later with ‘real’ companions are listed for several cluster galaxy populations, viz. undisturbed galaxies; undisturbed galaxies with HII emission; disturbed galaxies; and disturbed galaxies with HII emission.

As is seen, both populations of disturbed galaxies have a much higher (∼ 40–50%) fraction of galaxies with companions than the corresponding fraction (∼ 7%) for the populations of undisturbed galaxies. For both populations of disturbed galaxies, a χ² test gives the significance level for the observed fraction of galaxies with companions as compared to the remainder of the Sa + later population, as follows: disturbed galaxies, P = 5 × 10⁻¹⁰; and disturbed galaxies with HII emission, P = 2.1 × 10⁻³.

In previous work (see Papers IV and V) it was shown that galaxies classified as peculiar² show no tendency to have tidal companions, although a very high percentage (∼ 76 per cent) of these galaxies show compact emission, which is otherwise associated either with a bar, or with circum-nuclear starburst emission caused by galaxy–galaxy interactions. It was noted that a natural explanation for this result is that peculiar galaxies are predominantly on-going mergers in which the companion is already indistinguishable from its merger partner, and the compact emission arises from the starburst induced by the merger.

Accordingly, peculiar galaxies may also be considered to have ‘real’ companions, although in this case the companion has already begun merging with the galaxy. In Table 4 are listed the fractions of galaxies of the cluster galaxy populations which are either classified as peculiar, or which have a distinct visible companion. The fractions of both populations of disturbed galaxies with such mergers or companions is seen to be very high, and significantly larger than for the remaining Sa + later population, viz. disturbed galaxies.

² Note that galaxies were classified as ‘peculiar’ if their morphology was such that it could not be assigned a Hubble type; in contrast, galaxies of all types were noted as disturbed if their stellar distributions showed significant asymmetry or irregularity. For a more detailed description, see Paper IV.

Table 4. Disturbed galaxies of types Sa + later within the ensemble cluster (r ≤ vir). Galaxies with |v − v| > 4σ have been excluded.

| CGCG  | Comp. | Type | LH2/LH1 | Δv (arsec) | |Δv| (km s⁻¹) |
|-------|-------|------|---------|------------|---|-----------|
|       |       |      |         |            |   |           |
| 522-005 | C | pec | ... | 18 | ... |
| 522-063 | (C:) | S-Irr | ... | 134 | ... |
| 538-043 | * | pec | ... | 34 | 427 |
| 538-048 | * | C | pec | 0.9 | 134 | ... |
| 538-056 | * | C | pec | 6.3 | 34 | 427 |
| 539-025 | (C:) | SB | pec | 0.4 | 207 | ... |
| 539-029 | (C:) | S | pec | 0.1 | 86 | ... |
| 415-042 | (C:) | S: pec | 1.0 | 87 | 13 |
| 540-036 | S: pec | ... | 10 | 133 |
| 540-057 | S? | ... | 10 | 133 |
| 540-064 | C: SB | pec | 0.3 | 112 | ... |
| 540-090 | C: pec | ... | 10 | 133 |
| 540-093 | (C:) | Sb | pec | 0.9 | 110 | 79 |
| 541-112A | * | C | pec | ... | 10 | 133 |
| 541-011 | (C:) | SB:b: pec | ... | 139 | ... |
| 541-017 | pec | ... | 10 | 133 |
| 234-071 | (C:) | SB: pec | 0.3 | 160 | ... |
| 234-079A | C | S: pec | 1.4 | 23 | 38 |
| 234-079B | C | S: pec | 0.7 | 23 | 38 |
| 181-023 | C | S | pec | ... | 183 | 242 |
| 97-062 | C | Sa: pec | ... | 25 | 4 |
| 97-063 | S | pec | ... | 183 | 242 |
| 97-068 | (C:) | SBc pec | 0.4 | 158 | 2 |
| 97-079 | C | S? pec | ... | 183 | 242 |
| 97-087 | C | Sd pec | 4.5 | 183 | 242 |
| 97-093 | C | Sa: | ... | 183 | 242 |
| 97-102A | C | Sa | pec | ... | 183 | 242 |
| 97-122 | C | Sb pec | ... | 183 | 242 |
| 97-125 | C: (pec) | ... | 10 | 133 |
| 127-046 | (C:) | S(B)bc pec | ... | 10 | 133 |
| 160-064 | * | pec | ... | 183 | 242 |
| 160-075 | * | pec | ... | 183 | 242 |
| 160-100 | C | S | ... | 35 | 374 |
| 160-148A | C | S: pec | 2.7 | 21 | 207 |
| 160-148B | C | S: pec | 0.4 | 21 | 207 |
| 160-173 | S | ... | 183 | 242 |
| 160-179 | S: pec | ... | 183 | 242 |
| 160-180 | * | pec | ... | 183 | 242 |
| 160-191 | * | pec | ... | 183 | 242 |

Notes on individual objects:

522-005: companion in common envelope with galaxy; likely on-going merger.

522-063: = UGC 1387. UGC note: “Chaotic fragments of spiral arms. May be disturbed by companion”. There is a companion at Δv = 109 arcsec; however the velocity difference with the galaxy (∆v = 765 km s⁻¹) is rather high for a slow encounter.

538-043: R, Ho imaging shows that this is an interacting pair of galaxies in a common envelope.

538-048: the structure of this highly distorted galaxy in the R band is suggestive of an on-going merger. Accordingly the disturbance is more likely to be caused by this merger than by interaction with the listed companion.

538-056: “wispy ring [galaxy] with an elliptical companion located near the minor axis” (Horellou et al. 1995).
The galaxies NGC 2831/2832 = Arp 315 are close companions, but the velocity difference ($\Delta v \approx 900 \text{ km s}^{-1}$) between these and CGCG 181-023 = NGC 2830 is rather high for a slow encounter.  

97-079: CGCG note: double galaxy (Zwicky et al. 1960–68). The double structure is clearly visible in J,K and H imaging. These authors conclude that the complex kinematical behaviour, as well as a double nucleus can best be explained as two superposed interacting galaxies. This is the most likely explanation for the disturbance of this galaxy, rather than interaction with the listed companion in the Table.

97-093: There is a companion at $\Delta = 39$ arcsec, but the velocity difference between the two galaxies ($\Delta v = 714 \text{ km s}^{-1}$) is rather large for a slow encounter.

97-125: This galaxy was not classified as having a companion due to its large velocity difference with the presumed possible companion NGC 3860 ($\Delta v = 2676 \text{ km s}^{-1}$; see Paper IV). However the galaxy is interacting with CGCG 97-114, cf. Sakai et al. (2002).

127-046: this galaxy appears as a double galaxy in R, H$\alpha$ imaging. The double structure is even more clearly visible in J,K.

160-064: this galaxy is seen to have a double structure in Ho, J and K imaging.

160-075: This galaxy is close to NGC 4860 ($\Delta x = 37$ arcsec) but the velocity difference between the two galaxies ($\Delta v = 1456 \text{ km s}^{-1}$) is too great for a slow encounter.

160-140: “A striking emission is detected southwest of this galaxy—which suggests a close interaction with its neighbor DRCG 27-62.” (Bravo-Alfarro 2000).

160-180: J,K imaging shows that this is a double galaxy with the main galaxy and smaller companion in a common envelope. The double structure is very evident in Ho but only faintly visible in R.

160-191: “UCM1304+2907 MCG+05-31-133, the interactive fragmented system VV 841 and KUG1304+291, Irr Coma system with an embedded disc aligned near NS direction” (Vitiore et al. 1996).

Enhanced mergers

Firstly there are galaxies with close companions which have a small velocity difference, $|\Delta v| < 500 \text{ km s}^{-1}$, together with a low probability of being a chance superposition, $P > 0.05$ (see Paper IV). In column (3) galaxy types, again taken from Papers III and IV, are listed. Columns (4)–(6) of the Table give information on possible companions: the ratio of H-band luminosities of companion and galaxy, as indicative of the mass ratio (cf. Gavazzi et al. 1996); the angular separation from the galaxy; and (where known) the absolute velocity difference, $|\Delta v|$, with the galaxy. Since the main interest is to identify slow encounters, all possible companions with $|\Delta v| > 500 \text{ km s}^{-1}$ were excluded from the Table.

Detailed notes on a number of the galaxies are given below the Table. For a subset of the galaxies, R and narrow-band Ho imaging from the JKT and Nordic Optical Telescope on La Palma, and J,K imaging from UKIRT are available; these imaging data are being used for future studies of the survey galaxies (Thomas et al. 2006; Moss et al. 2006). From these images, evidence was found for double structure and/or interaction with a companion for a number of the galaxies (viz. CGCG 538-043, 538-048, 97-079, 127-046, 160-064 and 160-180; see notes below the Table).

From the data in Table 4 some 7 galaxies can be considered as ‘confirmed’ members of galaxy-galaxy interactions. Firstly there are galaxies with close companions which have a small velocity difference, $|\Delta v|$, together with a low probability of the companions being chance superpositions. (viz. CGCG nos. 540-112A, 97-102A, 234-079A and B, and 160-148A and B). In addition, CGCG 97-125 is in a well-studied interacting system (cf. Sakai et al. 2002).

There are an additional 11 galaxies which are probable components of interacting systems. These include galaxies with a double structure (viz. CGCG 522-005, 538-043, 538-048, 97-079, 127-046, 160-064 and 160-180); and galaxies which individual studies have shown to be probable members of an interacting system (viz. CGCG 97-087, 538-056, 160-140 and 160-191). Interestingly, four of the galaxies which have been revealed to have double structure by deeper imaging (viz. CGCG 522-005, 538-043, 160-064 and 160-180) are typed as peculiar, which gives support to the suggestion that peculiar galaxies are likely to be on-going mergers.

The combined number of galaxies with ‘confirmed’ and probable interactions and/or mergers is thus 46% of the disturbed galaxy sample. In addition, there are a further 7 galaxies which are possible members of interacting systems. These include galaxies with a close companion which has a low probability ($P < 0.05$) of being a projected com-
compared, although the velocity difference with the galaxy is not known (viz. CGCG 540-064 and 540-090); and galaxies with a companion which, while it has a significant probability \( (P > 0.05) \) of being a projected companion, its velocity difference with the galaxy is small (viz. CGCG 539-029, 415-042, 540-093, 234-071 and 97-068). Further galaxies which may be included as possible merger systems are those typed as peculiar but for which deeper imaging is not yet available (viz. CGCG 541-017 and 160-075). Including possible interactions and mergers, the combined percentage of the cluster disturbed galaxy sample which may belong to interacting/merging systems is thus 69%. It is to be noted that this percentage is in fact a lower limit, since further detailed study of individual objects may reveal additional interacting systems.

It is thus concluded that for \( \sim 50\% - 70\% \) or greater of the cluster disturbed galaxy population, their moderate or severe disturbance is likely to be due to galaxy-galaxy interactions associated with slow encounters.

4 DISCUSSION

4.1 Disturbed galaxies as the infall population

As noted in section 3.1, the infall population for the ensemble cluster is identified as (predominantly) comprising those cluster galaxies which have moderate or severe tidal disturbance of their stellar populations. This identification was made on the basis that these galaxies, which are mainly of type Sa and later (71% of the sample), have a higher velocity dispersion (\( \sigma = 1.42 \)) than all remaining cluster galaxies, with a value in good agreement with that expected for an infall population. Remaining cluster galaxies divided into samples of disturbed galaxies of types Sa + later, with and without emission, have velocity dispersions consistent with that for the cluster early-type galaxies (\( \sigma = 1.02 \)). Confirmation that the disturbed galaxy population is an infall population is provided by the relative distributions of early-type and disturbed galaxies in the r-v plane (see section 3.3).

The inner cluster region \( (r \leq 0.4r_{\text{vir}}) \) shows a sharp increase in the surface (and expected space) density of galaxies of types Sa + later, as compared to the lower, roughly uniform, surface density for \( r > 0.4r_{\text{vir}} \). Together with this change of surface density, there are notable changes in galaxy disturbance. The fraction of Sa + later galaxies which are disturbed doubles within the inner cluster region to \( \sim 30\% \) as compared to \( \sim 15\% \) for \( r > 0.4r_{\text{vir}} \). Moreover there is a 50% increase in the fraction of disturbed Sa + later galaxies which have HII emission from \( \sim 40\% \) for \( r > 0.4r_{\text{vir}} \) to \( \sim 60\% \) for \( r \leq 0.4r_{\text{vir}} \).

The galaxies which are included in the present survey are the relatively sparse population of giant (\( M_{B} \leq -18.5 \)) galaxies. For these cluster galaxies the relaxation times are quite short. The two-body relaxation time, \( t_{\text{r}} \), may be roughly estimated as,

\[
t_{\text{r}} \sim \frac{0.06N}{\ln(0.15N)} \times t_{d}
\]

where \( N \) is the number of cluster galaxies and \( t_{d} \) is the cluster crossing time (cf. Conselice, Gallagher & Wyse 2001).

For the individual clusters in the survey, \( t_{\text{r}} \sim t_{d} \) especially within the high density core region \( (r \leq 0.4r_{\text{vir}}) \) of the cluster. Since the infall population is not virialised, this suggests it is on first infall or, at the least, is a relatively recent arrival in the cluster. Furthermore the enhanced starbursts associated with this population tend to confirm this, since the disturbed galaxies evidently still retain substantial gas which may be expected to be stripped by tidal, ram-pressure and harassment effects by more prolonged exposure to the cluster environment.

4.2 Mergers and galaxy harassment

Many authors have attributed the transformation of cluster spirals to S0s to the effects of galaxy harassment, i.e. frequent high-speed galaxy encounters within the cluster. Notwithstanding the strong evidence for galaxy interactions and mergers (see section 3.4 above), can this mechanism explain the tidal disruption and associated circumnuclear starburst emission of the infalling galaxy population?

Originally, galaxy harassment was proposed as a mechanism to explain the origin of dwarf elliptical galaxies in clusters as remnants of harassed low-luminosity (e.g. \( L^{*}/5 \) and \( L^{*}/20 \)) bulgeless disc galaxies (Moore et al. 1996; Moore, Lake & Katz 1998). The effect of multiple close (\( d < 50 \) kpc) fast (\( \Delta v \sim 1500 \) km s\(^{-1}\)) encounters with giant cluster galaxies (\( L \geq L^{*} \)) on the fragile disc of such a galaxy was shown to drastically alter its morphology to resemble that of a dwarf elliptical. While galaxy harassment is able to describe the formation of dwarf galaxies as well as the fueling of low luminosity AGNs and the destruction of low-surface brightness galaxies in clusters, it is evident that this scenario is hardly applicable to the present sample of the cluster infall population. For a value of \( M^{*} = -20.5 \) (\( H_{0} = 70 \) km s\(^{-1}\) Mpc\(^{-1}\)) adopted by Moore et al. (1998), their most luminous model disc galaxy has an absolute magnitude, \( M = -18.8 \), which is fainter than most disturbed galaxies in the ensemble cluster (see Figure 12). Furthermore most of these disturbed galaxies are not bulgeless disc galaxies of types Sc–Sd as required by the model (see Figure 1).
In further work, Moore et al. (1999) discuss the effect of galaxy harassment on luminous \((L \sim L^*)\) disc galaxies. Their simulations show that luminous disc galaxies with a significant bulge component are stable against the effects of galaxy harassment. This makes it difficult to induce the non-axisymmetric structures in the discs of these galaxies which are required to provide the gravitational torques to drive gaseous inflow to fuel a central starburst. As Mihos (2004) has noted, it is hard to explain strong starburst activity in luminous spirals by galaxy harassment alone; rather fast encounters tend to trigger a modest disc-wide response of star formation. However, as has been seen above (see Figure 4), most (88%) of the detected HII emission in the disturbed galaxies of the infall population is classified as compact, which has been identified in previous work as most likely due to circumnuclear starburst activity (see Papers IV, V). These disturbed galaxies with compact emission are found more frequently in the cluster than in the field (see Paper V). Some 40% of disturbed galaxies show compact HII emission in contrast to only 17% of undisturbed galaxies of types Sa + later (see Figure 7). These results support a scenario of slow gravitational encounters for the disturbed galaxies rather than that of the fast encounters associated with galaxy harassment. (For further discussion, see Thomas et al. 2006).

One of the motivations for the development of the theory of galaxy harassment was the claim that, for faint disturbed disc galaxies in intermediate redshift \((z \sim 0.5)\) clusters, there was often no sign of an interacting companion, and that therefore an alternative explanation to such interactions was needed in order to explain the observed disturbance (cf. Moore et al. 1996). However, whatever may be the case for faint disc galaxies, there has never been any doubt that for giant cluster galaxies, interactions and on-going mergers in these intermediate redshift clusters are abundant (e.g. Lavery & Henry 1988; Lavery, Pierce & McClure 1992; Dressler et al. 1994a, 1994b).

Just as galaxy–galaxy interactions and mergers are common among the giant disc galaxy population in intermediate redshift clusters, so it has been shown above (section 4.1) that such interactions and mergers are frequent among the non-virialised infall population of low-redshift clusters and can provide a natural explanation for galaxy disturbance for a high proportion \((\sim 50-70\%)\) of the members of this population, without need of any recourse to explanations based on fast encounters, even supposing such explanations could account for the degree of disturbance observed. For the remaining members of this population without an obvious cause of disturbance, neither galaxy harassment nor undetected minor mergers can be ruled out. Nevertheless, it can be concluded that slow, rather than fast encounters are the predominant cause of the gravitational disruption of giant disc galaxies in low-redshift clusters.

### 4.3 Enhancement of galaxy–galaxy interactions and mergers in the infall population

The results obtained above imply an enhancement of galaxy–galaxy interactions and mergers in the cluster infall population as compared to the field. For the field population of Sa + later galaxies \((r > r_{vir}; n = 84)\), some 13% \((n = 11)\) are disturbed, and may be assumed to be in interacting or merging systems. In contrast, as has been seen, some \(\sim 50-70\%\) of the infall population are either interacting or merging with other galaxies. This is an enhancement by a factor of \(\sim 4-5\) compared to the field population and is statistically very significant \((\chi^2\text{ test, } P < 3 \times 10^{-7})\).

What is the cause of this enhancement of galaxy–galaxy interactions and mergers in the infall population? It is generally accepted that because of the high cluster velocity dispersion, the interaction/merger rate in (virialised) clusters is expected to be low (e.g. Ostriker 1980; Ghigna et al. 1998). What factors, associated with the infall population, could cause the interaction/merger rate to increase?

One expected difference between the infall population and the relaxed virialised population of the cluster is the predominance of galaxy groups in the infall population. These groups are likely to be subsequently destroyed by the tidal field of the cluster. Distortions of the orbits of galaxies in infalling groups by the tidal field of the cluster may increase galaxy–galaxy interactions (cf. Mihos 2004). Another suggestion, due to Sato & Martin (2006), is that group–group encounters in the infalling population could enhance galaxy–galaxy mergers. However it may be questioned whether either of these mechanisms alone would be capable of enhancing the interaction/merger rate by the large factor required.

A promising mechanism to greatly enhance the interaction/merger rate in the infall population is gravitational shocking as proposed by Struck (2005). Struck notes that cold dark matter simulations and observations are in good agreement regarding a common density profile across a range of structures from galaxy halos to the dark halos of large clusters. Moreover observations suggest that the central density decreases slowly with mass in dark matter halos. Accordingly for roughly comparable group and halo core densities, the passage of a group through the cluster core would substantially increase the instantaneous group halo mass. Since the typical core crossing time and group free-fall time are comparable, there is time for group galaxies to be pulled into a much denser and compact configuration. In the case that group and cluster core halo densities are roughly comparable, galaxies could be pulled in to roughly half their distance from the (group) core, increasing the galaxy density by nearly an order of magnitude and their collisions by a factor of 100 (density squared). In these encounters, dynamical friction will dissipate relative orbital energy, leading to galaxy–galaxy mergers. This mechanism would readily explain the enhanced galaxy interaction/merger rate found for the infall population of the ensemble cluster. The gravitational shocking discussed by Struck is for groups passing through the cluster core; clearly, infalling groups encountering any existing cluster sub-structure may also be expected to experience some degree of gravitational shocking. Thus infalling groups may be subject to a series of gravitational shocking events on their infall to the cluster centre, each contributing to the total interaction/merger rate.

In section 4.1 it was noted that disturbed HII ELGs have a higher velocity dispersion \((\sigma_v = 1.75)\) than for the entire sample of disturbed galaxies \((\sigma_v = 1.42)\). A similar effect is evident in comparing disturbed HII ELGs of types Sa + later with all disturbed galaxies of these types \((\sigma_v = 1.69, 1.55\) for the two samples respectively). Gravitational shocking may help to explain this effect. Since not only the frequency, but also the strength of encounters is de-
4.4 Transformation of spirals to S0s by unequal-mass and minor mergers

Theoretical studies have shown that major mergers of equal-mass galaxies can result in the formation of an elliptical galaxy with a de Vaucouleurs profile (e.g. Negroponte & White 1983; Barnes 1988, 1992; Hernquist 1992, 1993). In contrast, mergers of unequal mass spirals are expected to result in an S0 galaxy since the remnant retains significant rotation and disc destruction is not complete (e.g. Bekki 1998; Bendo & Barnes 2000; Cretton et al. 2001; Bekki et al. 2005). Alternatively, an S0 can be formed between the merger of a spiral and its satellite: the satellite can help to ‘sweep clean’ the disc of cold gas by means of a gravitationally induced bar driving gas to the nucleus, and the galactic disc is not destroyed, but thickened to one characteristic of an S0 (e.g. Toth & Ostriker 1992; Quinn, Hernquist & Fullager 1993; Mihos et al. 1995; Walker, Mihos & Hernquist 1996; Mihos 2004).

Thus the interactions and subsequent galaxy mergers identified in the Sa + later infall population of the ensemble cluster are potentially the precursors of some fraction of the early-type cluster population, most especially of the S0 population. What fraction of the present S0 population in low-redshift clusters can be accounted for in this way? Any such estimate is necessarily very uncertain, but it can be attempted as follows. In Figure 13 is shown the distribution of combined absolute magnitudes for the components of interacting and merging systems in the ensemble cluster (viz. the interacting and merging systems identified as ‘confirmed’, ‘probable’ and ‘possible’ in section 3.4 above). Also shown in the Figure is the absolute magnitude distribution of the S0 population of the cluster. The completeness limit for the S0 population is approximately, $M_B^0 = -19.1$. Following a merger, the resulting early-type remnant is expected to fade by $\sim 1–2$ magnitudes (cf. Larson & Tinsley 1978). Accordingly, the six interacting/merging systems with $M_B^0 \leq -20.6$ are expected to be potential precursors of early-type galaxies brighter than the completeness limit, $M_B^0 = -19.1$. The cluster tidal field can act to lengthen the merger time of interacting galaxies, and may even prevent mergers in the case of very loosely bound interacting pairs (cf. Makino & Hut 1997; Mihos 2004). On the other hand, this tidal field is likely to quickly strip loosely bound tidal debris associated with interacting galaxies, which may lead to an underestimation of the interaction rate (see Mihos 2004). For simplicity, these considerations will be neglected. Thus if it is assumed that the merger time $\sim 10^9$ years, then, for a uniform infall rate into the cluster, $\sim 60$ mergers are expected over the past 10 Gyr. However the infall rate is expected to be higher at earlier times (e.g. Ellingson et al. 2001). Accordingly if it is assumed that the mean integrated infall rate is twice the current observed rate, then $\sim 120$ early-type galaxies resulting from mergers are expected over the past 10 Gyr. Now the total number of S0 galaxies with $M_B^0 \leq -19.1$ in the ensemble cluster is 92. Thus if mergers are mainly unequal mass mergers and result predominantly in S0 galaxies, most of the S0 population can be readily accounted for as products of interactions and mergers in the cluster infall population.

5 CONCLUSIONS

Analysis of an ensemble cluster comprising a complete magnitude-limited sample of giant galaxies ($M_B^0 \lesssim -19$) in 8 low-redshift clusters has shown that disturbed galaxies in these clusters form an infall population. It has further been shown that the disturbance of the stellar populations of these galaxies can readily be explained by slow galaxy–galaxy encounters in at least 50–70% of cases. The resulting enhancement of slow encounters in the cluster infall population can be attributed to gravitational shocking (Struck 2005) of infalling galaxy groups. A simple estimate of the galaxy merger rate demonstrates that the cluster giant S0 population can be accounted for as the outcome of minor mergers over the past $\sim 10$ Gyr.

Notwithstanding this result, obviously not all cluster S0 galaxies need be products of merging galaxies in the infall population; some early-type cluster galaxies are expected to result from galaxy interactions in groups or the field (e.g. Zabludoff & Mulchaey 1998) and this may help explain the correlation between star formation and radial distance to several virial radii from the cluster centre (e.g. Lewis et al. 2002; Gomez et al. 2003; although for an alternative view, see Poggianti 2004). However, contrary to Balogh et al. (2004), it is not necessary to assume that the majority of cluster S0s have formed by such preprocessing in the field. Indeed the fact that most galaxies in the infall population are spirals (see section 4.4 above), rules out such
an explanation. Rather, the bulk of transformation of spirals to S0s takes place during, and as an inherent part of the process of virialisation of the infall population.

Moreover, at least for the cluster galaxies, other processes may play a significant role in the formation of cluster giant S0 galaxies. For the Virgo cluster, the majority of spiral galaxies have their Hα disks truncated most likely due to intracluster medium-interstellar medium (ICM-ISM) stripping as a cause of the reduced star formation (Koosmann & Kenney 2004). A similar effect has been found in other low-redshift clusters (Thomas et al. 2006). Such ram-pressure stripping of gas is likely to contribute to the transformation of cluster spirals to S0s. Nevertheless, as the present work has shown, it is plausible to suppose that for most cluster giant S0 galaxies their formation has involved slow galaxy–galaxy interactions and ensuing minor mergers.

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