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The ESO nearby Abell cluster survey[⋆]

IX. The morphology-radius and morphology-density relations in rich galaxy clusters

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ABSTRACT

We study the morphology-radius and morphology-density relations for a sample of about 850 galaxies (with $M_R \leq -19.5$) in 23 clusters from the ENACS (ESO Nearby Abell Cluster Survey). On the basis of their radial distributions we must distinguish: (i) the brightest ellipticals (with $M_R < -22$); (ii) the late spirals, and (iii) the *ensemble* of the less bright ellipticals, the S0 galaxies and the early spirals, which have indistinguishable distributions of projected radial distance R. The brightest ellipticals are most centrally concentrated, while the late spirals are almost absent from the central regions; the radial distribution of the other galaxy classes is intermediate. The previously found radial segregation of the ellipticals thus appears to be due to *the brightest ellipticals only*, while that of the spirals is due to *the late spirals only*.

The morphology-density (MD-) relation was derived with two measures of projected density: one using the 10 nearest neighbours (Σ_{10}) and another using only the nearest neighbour (Σ_1). In the Σ_{10} MD-relation, only the classes of early- and late-type galaxies show a significant difference, but the different galaxy types within those classes are indistinguishable. However, this result is affected by significant cross-talk from the morphology-radius (or MR-) relation, as Σ_{10} is strongly correlated with R. Σ_1 appears much less correlated with R and therefore the crosstalk from the MR-relation is much smaller. As a result, the normal "ellipticals" (with $M_R \geq -22$), the S0 galaxies and the early spirals *do have* different Σ_1-distributions. *On average*, the "normal" ellipticals populate environments with higher projected density than do the S0 galaxies while the early spirals populate even less dense environments.

We conclude that the segregation of the brightest ellipticals and the late spirals is driven primarily by *global* factors, while the segregation between "normal" ellipticals, S0 galaxies and early spirals is driven mostly by *local* factors. We discuss briefly the implications of these results in terms of scenarios for formation and transformation of galaxies in clusters.

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

1. Introduction

In the past thirty years many observers have studied the relation between morphology and cluster environment. Oemler (1974), Melnick & Sargent (1977) and Dressler (1980) were the first to quantify differences in the projected distributions of galaxies of various morphological types. Before this time it already was widely accepted that the Hubble classification reflects a sequence of physical properties. Yet, although the morphological classes appear to describe fundamental properties of galaxies, it is not very clear how those are determined by the (local or global) conditions in which a cluster galaxy finds itself.

Luminosity segregation (i.e. the fact that the projected distribution of galaxies within a cluster depends on luminosity) was found by Rood & Tunrose (1968), Capelato et al. (1980) and Kashikawa et al. (1998). In addition, Beisbart & Kesher (2000) found that bright galaxies are more strongly clustered than faint galaxies and Biviano et al. (2002, hereafter Paper XI) found that luminosity segregation is limited to the brightest ellipticals.

In addition, it was also found that there is a relation between morphological type and projected density. This morphology-density relation has been studied for local clusters (Dressler 1980; Goto et al. 2003) as well as at intermediate redshifts (e.g. Dressler et al. 1997; Fasano et al. 2000; Treu et al. 2003; Nuijten et al. 2005). Detailed studies of morphological segregation in clusters at low redshifts can provide a better understanding of the relations between the morphological classes. Prugniel et al. (1999) showed that galaxies likely to contain young sub-populations are preferentially found in less dense environments, while Goto et al. (2003) found that late disk galaxies avoid the dense central regions of clusters. At the same time, the fraction of gas-poor galaxies increases and the fraction of emission-line galaxies (ELG) decreases

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[⋆] Based on observations collected at the European Southern Observatory (La Silla, Chile).

towards the dense cluster center (Biviano et al. 1997, Paper III; Solanes et al. 2001; Dale et al. 2001; Thomas & Katgert 2006, Paper VIII).

The variation of the morphology-density relation with redshift adds information on the evolutionary relationships between cluster galaxies of different types and on possible transformation relations between them. On the one hand, Goto et al. (2003) argue that the morphology-density relations at $z = 0$ and $z = 0.5$ are very similar. On the other hand, Treu et al. (2003), who made a detailed study of the morphology-density relation in a cluster at $z = 0.4$, and Nuijten et al. (2005), who studied the morphology-density relation out to $z \sim 1$, find that the fraction of early-type galaxies in the overdense regions increases towards lower redshifts.

The latter studies thus confirm the findings of Dressler et al. (1997) and Fasano et al. (2000) that the fraction of S0 galaxies in clusters increases towards lower redshifts (but see Andreon 1998 and Fabricant et al. 2000). Results from e.g. Poggianti et al. (1999) and Jones et al. (2000) suggest that many early spirals have transformed into S0 galaxies, possibly by impulsive encounters (Moore et al. 1999). These results can be reconciled with the apparently passive evolution of most early-type galaxies if the progenitor bias is taken into account (van Dokkum & Franx 2001). Thus, early-type galaxies that underwent star formation at $z \sim 0.5$ (such as observed by Ferreras & Silk 2000) would not be identified as early-type galaxies at that redshift.

In studies of the (evolutionary) relationships between cluster galaxies of different types it is important to distinguish between local and global processes. Sanroma & Salvador-Solé (1990), and subsequently Whitmore et al. (1993) argued that the cluster-centric radius, a global parameter, is the most fundamental parameter, because they found a very strong correlation between morphology and cluster-centric radius. However, Dressler et al. (1997) argued that the morphology-density relation, which is probably the result of local processes, is more fundamental since it is observed for both regular and irregular clusters.

One of the reasons for these different conclusions may be that it is not trivial to separate global (radius) and local (density) segregation, as density and radius are generally correlated. Dominguez et al. (2001) tried to separate the two effects and concluded that in the inner regions of clusters, segregation seems to depend mostly on global parameters (cluster-centric radius or mass density), while in the outer region of clusters segregation can be best described by local parameters, such as projected galaxy density.

In this paper we use the galaxy types derived by Thomas & Katgert (2006, Paper VIII) for galaxies in the ENACS clusters to revisit the question of global vs. local driving of segregation. Since our data are mostly limited to the central regions of rich clusters (they do not extend much beyond the virialization radius) our analysis is largely complementary to those of Goto et al. (2003) and Treu et al. (2003) whose data go out to much larger projected distances. The paper is organised as follows. In Sect. 2 we summarize the data that we used, in Sect. 3 we study the morphology-radius relation, and in Sect. 4 we investigate the morphology-density relation. Finally, we discuss the results and summarize our conclusions in Sect. 5.

2. Data sample

The present discussion is based on data from the ESO Nearby Abell Cluster Survey (ENACS for short; see Katgert et al. 1996, 1998 – Papers I and V). In order to have a cluster sample that is essentially volume-limited, we imposed a redshift limit of $z < 0.1$ (see e.g. Paper II, Mazure et al. 1996). Interlopers (non-members) were eliminated with the interloper removal procedure devised by den Hartog & Katgert (1996) as slightly modified by Katgert et al. (2004, Paper XII). We accepted only clusters with at least 20 member galaxies.

Like Dressler (1980) and Whitmore et al. (1993) we applied a limit in absolute magnitude, which was defined as follows. In Paper V the ENACS spectroscopy was estimated to become significantly incomplete below $R \sim 17$. Using this limit, we find that 33 of our clusters could be completely sampled down to $M_R = -19.5$ ($H_0 = 100$ km s^{-1} Mpc^{-1}). For 21 of these clusters, Katgert et al. (1998) compared the magnitude distributions of the galaxies with ENACS redshifts with that of the general galaxy population in the direction of the clusters, as derived from the EDSGC catalogue produced with Cosmos (e.g. Collins et al. 1989). From the Cosmos data, 4 of these 21 clusters appeared not to be sampled down to $M_R = -19.5$, so we excluded those. The projected galaxy density, in the ENACS dataset, of the 4 rejected clusters was subsequently used as a guide to the identification of those 3 clusters among the 12 without COSMOS data, that are likely to be incomplete down to $M_R = -19.5$, and which were therefore excluded.

We used the galaxy types derived in Paper VIII, from CCD-imaging and/or from the ENACS spectrum. Among the selected clusters, there are 3 with galaxy types for less than 80% of the galaxies, and these were not used. We are thus left with a sample of 23 clusters, with 1118 member galaxies, for 1105 of which a galaxy type was estimated, and this cluster sample is described in Table 1.

In Paper VIII a full description is given of the classification method, and we refer to that paper for details. In summary, we used CCD images of 2295 ENACS galaxies to estimate their morphological type. In addition, we used the spectral types determined by de Theije & Katgert (1999, Paper VI) from a PCA/ANN analysis of the ENACS spectra, after those had been recalibrated with the (mostly new) morphological types. Finally, we combined all this information (including also morphological types from the literature), using a set of calibrated prescriptions for those galaxies with both a morphological and a spectral type. The inclusion of spectral types is, strictly speaking, at odds with the terms morphology-radius and morphology density relation, but as we argued in Paper VIII the galaxy types derived there form a consistent set.

In the present analysis we mostly use the combined morphological and spectral types, which can be one of the following: E(lliptical), S0 (galaxy), Se (early spiral, i.e. either Sa, Sab or Sb) and Sl (late spiral, i.e. either Sbc, Sc, S/I or I). However, in a few cases, we will limit ourselves to galaxies with morphological types. Note that we do not use the galaxies with mixed types (E/S0, S0/S) nor the generic spirals (Sg). Because it was found, in Paper XI, that the brightest ellipticals (or Eb, i.e. those with $M_R < -22$) show luminosity segregation, we did

Table 1. The 23 ENACS clusters with galaxy samples complete to $M_R = -19.5$ ($H_0 = 100\ \mathrm{km\,s^{-1}\ Mpc^{-1}}$).

ACO	cz_{3K}	σ_V	Center	$N_{\rm memb}$	$N_{\rm type}$
87	16 149	875	Geometric	17	17
119	12 997	744	X-ray	63	62
151	12 074	399	Density peak	15	15
151	15 679	693	X-ray	37	37
168	13 201	524	X-ray	50	50
548E	12 400	706	X-ray	43	43
548W	12 638	819	X-ray	53	52
754	16 754	769	X-ray	38	38
957	13 661	691	X-ray	24	24
978	16 648	497	cD-galaxy	51	47
2040	13 974	602	X-ray	31	31
2052	10 638	654	X-ray	25	22
2401	16 844	475	cD-galaxy	23	22
2734	18 217	579	X-ray	38	38
2799	18 724	493	cD-galaxy	34	34
3122	19 171	780	Density peak	61	61
3128	17 931	809	X-ray	145	145
3158	17 698	977	X-ray	87	85
3223	17 970	597	cD-galaxy	53	52
3341	11 364	561	X-ray	25	25
3528	16 377	1040	X-ray	28	28
3651	17 863	662	cD-galaxy	78	78
3667	16 620	1064	X-ray	99	99

The columns give: the ACO number, the average velocity of the cluster in the CMBR reference frame (cz_{3K} in $\mathrm{km\,s^{-1}}$), the global velocity dispersion of the cluster (σ_V in $\mathrm{km\,s^{-1}}$), the way in which the center of the cluster was determined, the number of member galaxies in this sample ($N_{\rm memb}$), and the number of member galaxies in this sample with a galaxy type ($N_{\rm type}$), either from CCD-imaging and/or from the spectrum.

Table 2. The number of galaxies with morphological and spectral types.

Galaxy type	All	Morph.
Eb	24	24
E	149	149
S0	438	337
Se	130	110
Sl	117	55

not include those in the present analysis either, except to confirm their strong radial segregation. For the sake of consistency we also excluded all galaxies of other types with $M_R < -22$).

In Table 2 we show the number of galaxies within each class, as well as the number for which the type is morphological. The spectral types do not add much information for ellipticals and early spirals, because the spectra of these galaxy types are not very, or not at all, discriminative. On the contrary, the spectra of S0 galaxies and, in particular, Sl galaxies provide fairly good to very good discrimination.

3. The morphology-radius relation

As was already mentioned in Sect. 1, morphological segregation has two aspects, viz. one related to global factors and another related to local conditions. We first analyze the evidence for a global morphology-radius relation by comparing radial distributions of the various galaxy classes. We quantify these comparisons through Kolmogorov-Smirnov (KS-) tests. The KS-test gives the probability, $P_{\rm KS}$, that two distributions are drawn from the same parent distribution.

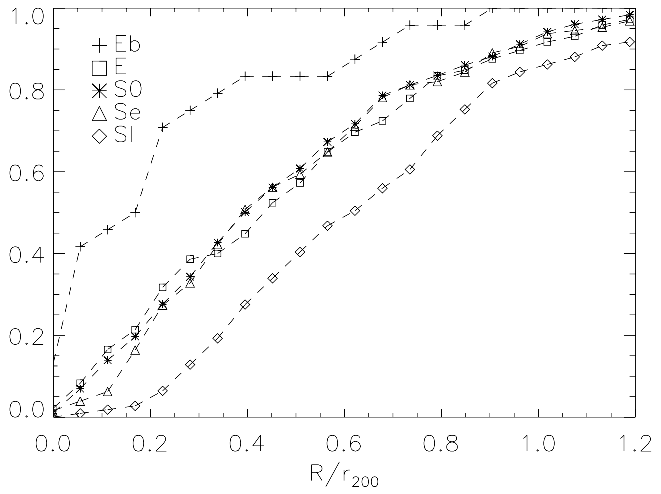

Fig. 1. The morphology-radius relation. We show the cumulative radial distribution for the 5 galaxy types: Eb (ellipticals with $M_R < -22$), E (other ellipticals), S0 galaxies and early and late spirals (Se and Sl). The radial distributions of Eb and Sl galaxies are significantly different from the three other distributions.

We adopted the center of each cluster as in Paper XI. The cluster center position is either the X-ray center, the position of the central cD galaxy, the position of the peak in the projected density, or the geometric center (see Table 1). The projected distance to the cluster-center, R, can be scaled in different ways. Whitmore et al. (1993, hereafter WGJ) adopted a scale radius within which the average projected density drops below a certain value. Instead, we scaled the cluster-centric radius with r_{200}, which is the radius within which the average density is 200 times as large as the critical density of the Universe, and which is closely related to the virialization radius (Navarro et al. 1996). Although r_{200} cannot be measured directly from the data, a good approximation is $r_{200} = \sqrt(3)\sigma_V/(10H(z))$, where σ_V is the global velocity dispersion of the cluster and $H(z)$ is the Hubble parameter at redshift z (see e.g. Carlberg et al. 1997). The global velocity dispersion σ_V was taken from Paper XI and is listed in Table 1.

In Fig. 1 we show the morphology-radius relation. Note that the results in Fig. 1 use galaxies with morphological *and* spectral types. Dressler et al. (1980) and WGJ used the E, S0 and S classes in their segregation studies, without subdividing the ellipticals and spirals, as we do. However, Fig. 1 clearly shows that the morphology-radius relation is primarily due to the *brightest* ellipticals (Eb), which are centrally concentrated, and the *late* spirals (Sl) which are almost absent from the central region ($R > 0.2r_{200}$). There is no evidence that the "normal" ellipticals (E), S0 galaxies and early spirals (Se) have different radial distributions, although their radial distributions are

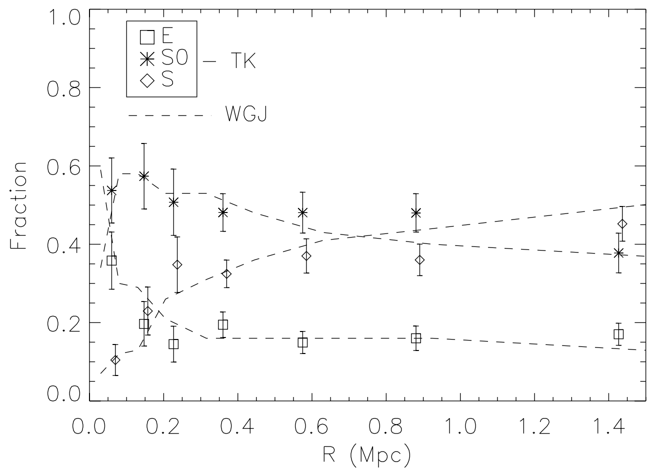

Fig. 2. The morphology-radius relation, expressed as the fraction of galaxies of different types for various projected distances (with H_0 = 100 km s^{-1} Mpc^{-1}) . The dashed lines were taken from Fig. 4 in WGJ, and the symbols represent our results.

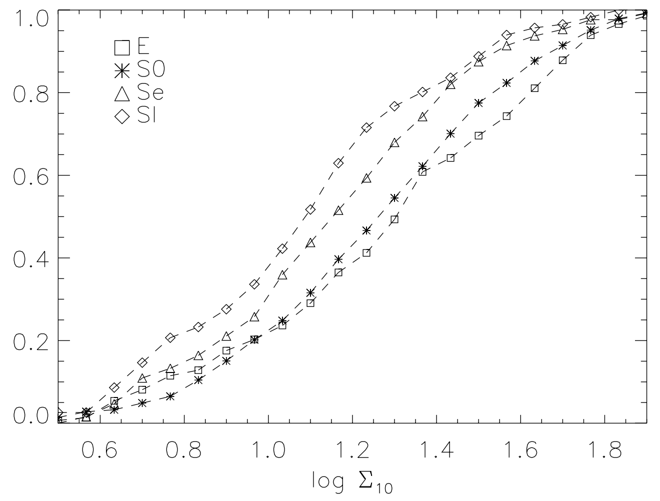

Fig. 3. The morphology-density relation using Σ_{10}, the projected density derived from the 10-th nearest neighbour. We show the cumulative distribution of Σ_{10} for the various galaxy classes. Note that the brightest ellipticals are not included in the elliptical class.

Table 3. The results of the MR comparisons.

Galaxy samples	$P_{\rm KS}$	
	All types	Morph. types
Eb – E	<0.01	<0.01
Eb – S0	<0.01	<0.01
Eb – Se	<0.01	<0.01
Eb – Sl	<0.01	<0.01
E – S0	0.49	0.50
E – Se	0.32	0.23
E – Sl	<0.01	<0.01
S0 – Se	0.33	0.33
S0 – Sl	<0.01	<0.01
Se – Sl	<0.01	0.03

significantly different from those of bright ellipticals and late spirals.

In Table 3 we show the results of the KS comparisons between the various galaxy classes (for all galaxies as well as for those with morphological types only). If we limit the comparisons to galaxies with morphological types, we obtain essentially identical results as when we use all galaxies. Only the Se – Sl comparison now yields a KS-probability of 0.03 instead of <0.01 , probably mostly due to the much smaller number of Sl involved (cf. Table 2).

In Fig. 2 we compare our morphology-radius relation with the one derived by WGJ. Note that in this comparison, we use the result of WGJ as expressed in Mpc (but corrected to the value of the Hubble constant that we use), and using our unscaled projected radii R in Mpc. For this comparison we included the brightest ellipticals in the E class and we combined all spirals, i.e. Se, Sl and generic spirals. As a result, we have 173 ellipticals, 438 S0 galaxies and 316 spirals (because here we could also include the *generic* spirals). Figure 2 shows that the agreement between the MR-relations of WGJ and ours is quite good, although WGJ have a slightly higher fraction of spirals in the outer regions, but not significantly so. Yet, the fact that WGJ had a fainter magnitude limit (by 0.5 mag), so that they were able to detect relatively more (faint) Sl galaxies, may be (partly) responsible for the slight difference. It is especially noteworthy that the agreement for the ellipticals is also quite good in the central regions (say, for $R < 0.4$ Mpc). This shows that the segregation of the early-type galaxies is indeed primarily due to the brightest ellipticals (which are largely responsible for the upturn within ~0.1 Mpc), even though there is on average only one of those in each cluster.

4. The morphology-density relation

We now turn to the analysis of the local factors in morphological segregation, by studying the morphological composition as a function of projected density. For the determination of the morphology-density relation, we first followed Dressler's (1980) prescription, i.e., we used the 10 nearest neighbours (in projection) of each galaxy to determine the projected density, Σ_{10}. In Fig. 3 we show the morphology-density relation, viz. the cumulative distributions of the galaxies of various types with Σ_{10}. As explained before, we did not include the brightest ellipticals. Note that the results in Fig. 3 use galaxies with morphological *and* spectral types. The results of the KS comparisons of the Σ_{10}-distributions are given in Table 4.

Figure 3 and Table 4 show that the ellipticals, S0 galaxies and early spirals, which have indistinguishable radial distributions, do not all have the same distribution of projected density Σ_{10}. From Fig. 3 it appears that the average Σ_{10} decreases monotonically from early-type to late-type galaxies. However, only the comparisons between early and late types (i.e. E or S0 on the one hand and Se or Sl on the other hand) show a significant difference. If we limit the comparison to galaxies with morphological types, the Sl become slighly less different, probably as a result of the smaller number of Sl involved (see the last column in Table 2). However, the general result does not

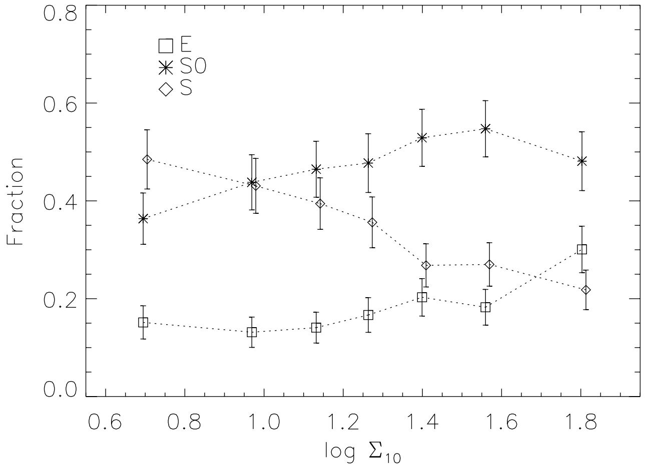

Fig. 4. The morphology-density relation in the traditional representation, i.e. as the variation of the fraction of galaxies of different morphological types with projected density Σ_{10}.

Table 4. The results of the Σ_{10} MD comparison.

Galaxy samples	P_{KS}	
	All types	Morph. types
E – S0	0.33	0.57
E – Se	<0.01	<0.01
E – Sl	<0.01	0.02
S0 – Se	<0.01	<0.01
S0 – Sl	<0.01	0.09
Se – Sl	0.07	0.96

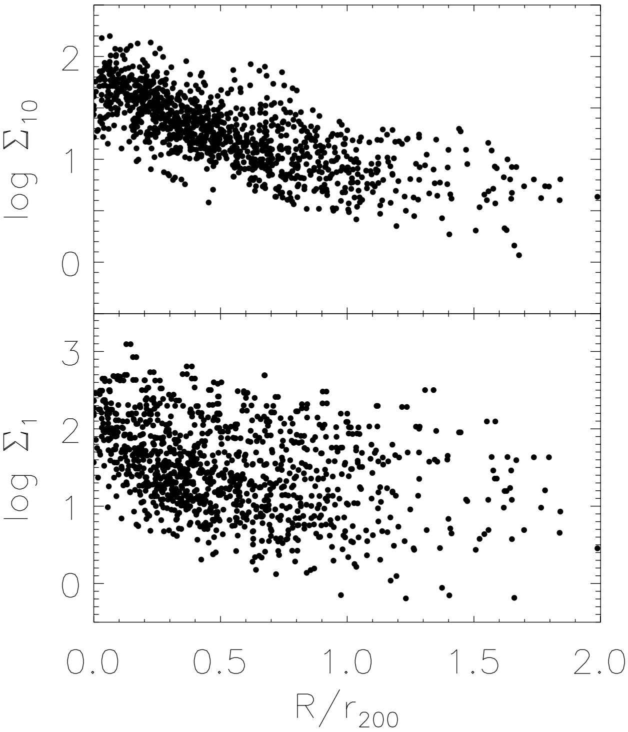

Fig. 5. The distribution of the galaxies w.r.t Σ_{10} and R/r_{200} (*top*) and Σ_1 and R/r_{200} (*bottom*). Σ_{10} is the projected density derived from the 10-th nearest neighbour while Σ_1 is derived from the projected distance to the nearest neighbour.

change: early- and late-type galaxies appear to have different Σ_{10}-distributions.

In Fig. 4 we show our result in the more traditional fashion, i.e., as the dependence of the fractions of galaxies of different morphological types on projected density Σ_{10}. A detailed comparison of this figure with similar figures in the literature requires a detailed calibration of the zero-point of the projected densities. The latter depends on the lower limit in absolute magnitude, and on the photometric band in which this is defined. We refrain from a calculation of such zero-point offsets, but we note that the agreement between our result and that of Dressler (1980) is very good if our densities were about $10^{0.15}$ smaller than Dressler's, which is quite plausible.

Comparison with the MDR obtained by Goto et al. (2003), obtained from the SDSS is even more interesting but, at the same time, less straightforward. More interesting because Goto et al. also distinguish early and late disc galaxies, like we do. However, less straightforward because their morphological types, which were derived in an automated fashion from the SDSS images, are: early, intermediate, early disc and late disc. It is not at all trivial to relate these types to ours, viz. elliptical, S0, early and late spiral. Judging from their Fig. 12, and comparing with Fig. 4, their early-type galaxies could correspond mostly to our ellipticals. However, their intermediate-type galaxies probably represent only a fraction (of the order of two-thirds) of our S0 galaxies, which leaves the correspondence between their early and late discs with our early- and late-type spirals ill-defined.

Returning now to Fig. 3, we stress that it must be realized that Σ_{10} is correlated with radius through the projected number density profile of the galaxy population. Thus, Σ_{10}-distributions of two galaxy samples can be different as a result of differences in radial distribution. In the upper panel of Fig. 5 we show the correlation between Σ_{10} and R/r_{200}, which appears to be quite strong. Apparently, Σ_{10}, which was designed to measure the local projected density, is still a rather global parameter. Therefore, we defined an alternative measure of the local projected density as $\Sigma_1 = 1/(\pi d^2)$, where d is the projected distance to the nearest neighbour. While Σ_1 is more affected by Poisson noise than Σ_{10}, the lower panel of Fig. 5 shows that it also varies less with R/r_{200} than Σ_{10}, at least for $R \gtrsim 0.2 r_{200}$.

One might wonder to what extent Σ_1 might be susceptible to imperfections in the interloper removal (see Katgert et al. 2004). It is difficult to quantify that in an exact manner, but from Fig. 7 in that same paper, we conclude that the errors in the interloper removal must be very minor. In addition, the interloper removal is done without information on galaxy type, so we would expect these very minor errors to produce random noise in the morphology-density relation. Below we will discuss the consequences of the noisy nature of Σ_1.

In Fig. 6 we show the morphology-density relation using Σ_1 instead of Σ_{10}. Note that we used galaxies with morphological *and* spectral types. As for Σ_{10}, the average Σ_1 appears to decrease monotonically from early-type to late-type galaxies,

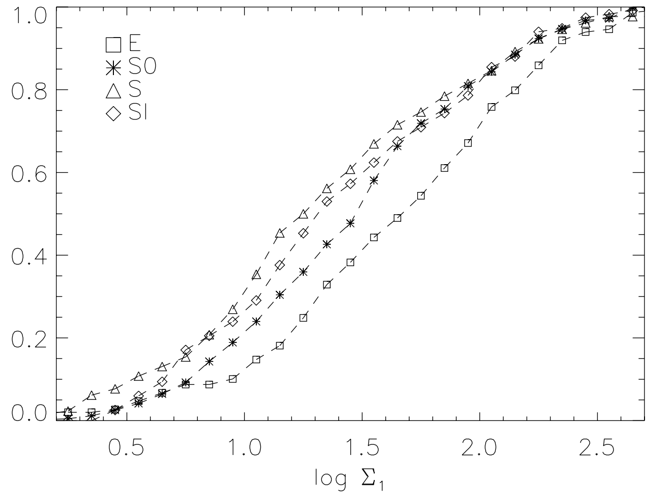

Fig. 6. The morphology-density relation using Σ_1, the projected density derived from the nearest neighbour. We show the cumulative distribution of Σ_1 for the various galaxy classes.

except for the late spirals, which are intermediate between the S0 galaxies and the early spirals. The results of the KS comparisons are given in Table 5. The late spirals are indeed not very different, if at all, from the other three classes, and certainly *much less* so than in the morphology-radius relation. The other three galaxy classes are found to have significantly different Σ_1-distributions. It is important to realize that this result cannot be affected by cross-talk from the morphology-radius relation, since the radial distributions of E, S0 and Se galaxies were found to be indistinguishable.

In view of the novelty of Σ_1, and the rather large noise in it, we have checked the robustness of our conclusions. We have done this by repeating our analysis for a set of 1000 azimuthal scramblings of our cluster sample. By leaving the radial distribution unchanged, we have avoided introducing unwanted cross-talk from the MR-relation. At the same time, the azimuthal scrambling will destroy the relations between morphological type and local projected density, as found in Fig. 6 and Table 5. In other words: if the strong dissimilarities of the Σ_1-distributions of ellipticals, S0 galaxies and early spirals are real we would expect that in the scrambled data the low values of the KS-probabilities that we observed ($P_{\rm KS} < 0.01$) are very rare.

The results of the 1000 scramblings indeed fully confirm this expectation. Only in 2 out of 1000 cases does the E – S0 comparison give $P_{\rm KS} < 0.01$, while for the E – Se and the S0 – Se comparisons the corresponding fractions are 28 and 29 out of 1000. This result indicates that notwithstanding the fairly large Poisson noise in Σ_1, our results about segregation in Σ_1 are robust.

From the cumulative distributions shown in Figs. 1, 3 and 6 we conclude that the various classes of galaxies obey different segregation rules. It is evident that position in the cluster (i.e. projected distance from the center) is the main factor that sets the brightest ellipticals and the late spirals apart. On the contrary, the differences between ellipticals, S0 galaxies and early spirals are most apparent in their distributions of projected density, either Σ_1 or Σ_{10}, or both. The segregation of ellipticals, S0 galaxies and early spirals is therefore probably driven primarily by local conditions, while that of late spirals and brightest ellipticals seems primarily driven by global conditions.

Table 5. The results of the Σ_1 MD comparison.

Galaxy samples	$P_{\rm KS}$	
	All types	Morph. types
E – S0	<0.01	<0.01
E – Se	<0.01	<0.01
E – Sl	<0.01	0.12
S0 – Se	<0.01	<0.01
S0 – Sl	0.19	0.96
Se – Sl	0.50	0.03

5. Discussion and conclusions

For about 850 galaxies in 23 ENACS clusters we studied morphological segregation in projected radius and projected density. The sample of galaxies is complete to a magnitude $M_R = -19.5$ ($H_0 = 100$ km s^{-1} Mpc^{-1}).

Our analysis has yielded two main results. First, the distribution of projected radius (i.e. the morphology-radius relation) shows that the brightest ellipticals (i.e. those with $M_R < -22$) and the late spirals have distributions that are significantly different from those of the other ellipticals (with $M_R \geq -22$), the S0 galaxies and the early spirals. The latter three galaxy classes have indistinguishable radial distributions, which are intermediate to that of the brightest ellipticals (very centrally concentrated, with 75% of the brightest ellipticals within 0.3 r_{200}) and that of the late spirals (of which only 15% have $R < 0.3\ r_{200}$).

Secondly, the morphology-density relation shows that the ellipticals, S0 galaxies and early spirals have significantly different distributions of local density Σ_1. On average, ellipticals prefer environments where the density is highest, while early spirals avoid these environments. The behaviour of S0 galaxies is intermediate; they are present in low density as well as high-density environments. The fact that the ellipticals and S0 galaxies have indistinguishable distributions of the less local density Σ_{10}, is due to the significant correlation between Σ_{10} and projected radius R.

The first result suggests that for the brightest ellipticals and for the late spirals global effects, such as position in the cluster, are more important than the properties of the local environment. On the contrary, the second result suggests that for the ellipticals, S0 galaxies and early spirals the position in the cluster is much less important than the local conditions. Note that the latter result does not suffer from cross-talk from the radial distribution, as the three classes have essentially identical R-distributions.

Although radial segregation was observed before, the new result of our analysis is that only *the brightest* ellipticals and the *late* spirals show segregation, while the other ellipticals and the early spirals do not. In the SDSS data discussed by Goto et al. (2003) a similar difference between what they refer to as "early and late disks" is visible. On the other hand, the strong increase towards the center of the fraction of ellipticals found by Goto et al. is probably mostly due to the fact that they do not consider the brightest ellipticals separately, as should be done (see Paper XI).

The present analysis shows that the distinction between global and local segregation is not simply a matter of inner regions vs. outer ones, as one might have concluded from the results obtained by Dominguez et al. (2001). The different segregation "rules" that they find for the inner and outer regions appear to be manifestations of different segregation behaviour of the various types of galaxies.

Our conclusions provide confirmation of several current ideas about galaxy evolution and transformation in clusters of galaxies. These ideas distinguish between two different kinds of processes: formation of galaxies through mergers of smaller galaxies, or transformation of galaxies through encounters with other galaxies or by the influence of the cluster potential. We now describe briefly how our results may give information about these processes, taking the several galaxy classes one at a time, from early to late Hubble types.

The segregation of the *brightest ellipticals* was investigated by several authors (e.g. Rood & Tunrose 1968; Capelato et al. 1981; Kashikawa et al. 1998; Beisbart & Kesher 2000 and in Paper XI). Those studies indicate that the brightest ellipticals have been (and are being) formed probably by merging and accretion in the central regions of clusters (see e.g. Governato et al. 2001). Global estimates of the time-scale involved in the accretion, viz. that of dynamical friction, show that only in the central regions this time-scale is sufficiently short that this process may be important.

Most of *the other ellipticals* have probably formed by merging of disk galaxies (e.g. Toomre & Toomre 1972; Barnes & Hernquist 1996; Aguerri et al. 2001). Direct evidence for mergers was found in high-redshift clusters (e.g. Lavery & Henry 1988; Lavery et al. 1992; Dressler et al. 1994; Couch et al. 1998; van Dokkum et al. 1999). In the hierarchical scenario, the formation of ellipticals thus takes place in relatively dense regions (proto-clusters) where there were enough objects that could merge. Therefore, it is not surprising that we find few ellipticals in regions with low projected densities.

The *S0 galaxies* and *early spirals* must be discussed together as they are likely to be related through transformation processes. Several mechanisms are thought to be important in the evolution and transformation, such as the stripping of gas, impulsive tidal interactions between galaxies and mergers. These have been described in papers by e.g. Moore et al. (1998, 1999), Abadi et al. (1999) and Okamoto & Nagashima (2001). It appears that impulsive encounters of early spirals with other galaxies may lead to stripping of a modest fraction of the stellar component and an increase of the vertical scale-height of the disk.

Several studies have shown that S0 galaxies, like ellipticals, are passively evolving galaxies, which mainly contain stars formed at high redshifts (e.g. Bower et al. 1992; Ellis et al. 1997; Lucey et al. 1991; van Dokkum et al. 1996, 1998). However, it should be remembered that shorter luminosity-weighted ages were found for faint S0 galaxies (e.g. Smail et al. 2001). At the same time, evidence has accumulated that the fraction of S0 galaxies in clusters has increased strongly since $z = 0.5$ (Dressler et al. 1997; Fasano et al. 2000), and this is generally thought to be due to a transformation from early spirals into S0 galaxies.

Poggianti et al. (1999) discuss the evidence for spectral and morphological transformations of early spirals into S0 galaxies. At intermediate redshifts starformation in spirals is probably quenched after a final starburst (e.g. Dressler & Gunn 1983; Couch & Sharples 1987), which leads to a spectral transformation. This process occurred when galaxies fell into the cluster (Dressler et al. 1999; Poggianti et al. 1999; Ellingson et al. 2001). The process that transformed early spirals into S0 galaxies probably occurred later and on longer time-scales (see also Poggianti et al. 1999; Jones et al. 2000). One process by which the starformation could be quenched is the removal of the gas in spiral galaxies by ram pressure and turbulent or viscous stripping through the hot intra-cluster medium (Quilis et al. 2000).

Harassment and impulsive encounters (Moore et al. 1998) are most likely the processes by which early spirals can be transformed into S0 galaxies. This is supported by our finding that, on average, the local density around early spirals is somewhat smaller than that around S0 galaxies. The transformation efficiency is likely to be larger if the density is higher, and this would lead to a selection against early spirals in higher density environments. Biviano & Katgert (2004, Paper XIII) studied the velocity distributions of the various galaxy classes and concluded that those also provide marginal support for this picture.

Finally, while the brightest ellipticals are found exclusively in the central regions of clusters, the *late spirals* avoid those regions almost completely. This suggests that the late spirals are probably destroyed by the tidal forces of the cluster potential. As shown by Moore et al. (1999), the fate of spiral galaxies in the central regions of clusters depends very much on the "hardness" of their gravitational potential. The "destruction hypothesis" for late spirals is therefore very plausible because their rotation curves indicate that their mass distributions are much less centrally concentrated that those of early spirals (e.g. Corradi & Capaccioli 1990; Biviano et al. 1991; Adami et al. 1999; Dale et al. 2001).

We refrain from estimating relevant timescales and efficiencies of the various processes mentioned here. However, we note that Treu et al. (2003) have made such estimates by defining three distinct regimes in a cluster according to the different physical processes that drive the various types of segregation.

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