

The morphological segregation of galaxies in clusters

II. The properties of galaxies in the Coma cluster^{*}

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Abstract. We have looked for differences in the galaxy properties along the Hubble sequence and for the dependence of these properties on the environment, in an absolute magnitude complete sample of 187 galaxies in the Coma cluster. The morphological type of all galaxies was determined from our own high resolution data. We also compared this sample with other published complete samples of galaxies in the Perseus and Virgo clusters and in the local field.

Ellipticals and lenticulars are highly homogeneous in all their internal photometric properties. These galaxies are well described just by their morphological type and luminosity, regardless of the environment. On the other hand, some of the external properties of these galaxies and of their subclasses differ markedly. Then, for early-type galaxies, the environment determines the space density of each type but not the internal properties of the type, which are the same in all environments.

Spirals form a heterogeneous class of objects whose photometric properties depend on one extra parameter. As a result, spirals that are blue in the optical also have blue ultraviolet-optical colors, higher mean surface brightness (or smaller radii) for their magnitude, strongly avoid the cluster center and have high velocities relative to the cluster center. The spatial distribution of spirals as a whole class is uniform. For spirals, therefore, the environment does not determine the space density, which is the same in all environments, but strongly affects the internal galaxy properties.

The galaxies in Coma, as in Perseus, are segregated primarily with respect to the supercluster main direction, thus providing a new interpretation of the morphology-radius and morphology-density relations.

Finally, the NGC 4839 group is richer in early-type galaxies than other regions at the same distance from the cluster center, showing that the morphological segregation could be a useful tool for discriminating fortuitous alignments from real groups.

Key words: galaxies: elliptical and lenticular, cD – spiral – fundamental parameters – luminosity function, mass function – interactions – cluster: individual: Coma cluster

1. Introduction

The study of the morphological dependence of galaxy properties is one of the major challenges of observational astronomy, since it can offer clues for understanding galaxy formation and evolution and is also central to many problems in cosmology (e.g. galaxy counts).

It is common wisdom that ellipticals crowd the central region of clusters, whereas spirals populate the cluster outskirts and the field (e.g. Hubble & Humason 1931, Dressler 1980b, Postman & Geller 1984, Sanromà & Salvador-Solé 1990, Whitmore, Gilmore & Jones 1993). Galaxy optical (e.g. Hubble & Humason 1931 and, for UBVR colors, Holmberg 1958) and ultraviolet (2000 Å, Donas, Milliard & Laget 1995) colors depend on the morphological type and the same holds for the luminosity function (Sandage, Binggeli & Tammann 1985), and many other galaxy properties (e.g. HI content). Near infrared (JHK) colors of Es and S0s are similar within the error bars, (Recillas-Cruz et al. 1990), as well as infrared colors of the Ss stages (sub-types) (Gavazzi & Trinchieri 1989) separately.

However the real situation is complex. One widely debated question concerns the fundamental parameter determining the galaxy type and therefore the observed morphological segregation. Whitmore, Gilmore & Jones consider that it is the distance from the cluster center, Dressler and Postman & Geller that it is the local density, while others (Sanromà & Salvador-Solé 1990, Andreon 1994) state that the present data and analyses do not allow one to distinguish between the two possibilities.

Several other important questions still call for an answer.

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– Does the environment determine the density of each morphological type (and therefore the relative spatial distribution without altering the galaxies' internal properties) or does it modify the morphological type of the galaxies in such a way as to induce the observed morphological segregation?

– Is the scatter in optical colors in each morphological class intrinsic and independent of the environment (Visvanathan & Sandage 1977), is it related to the galaxy environment (Larson, Tinsley & Caldwell 1980; using part of the data listed in Visvanathan & Sandage 1977), or is it largely due to errors in the type assignment or to an incorrect determination of galaxy distances?

– Are the luminosity functions of boxy and disk ellipticals different (Bender et al. 1989), or not (Andreon 1994)? What is the relative spatial distribution of the two classes: are boxy ellipticals preferentially found in high density regions and disk ellipticals in low ones (Shioya & Taniguchi 1993, Caon & Einasto 1995) or is their distribution density independent, as in the Perseus cluster (Andreon 1994)?

In order to give some insight into these and other questions, we have been conducting an observing program of galaxies in different environments, including nearby (apparently) relaxed clusters (Coma and Perseus), nearby clusters with evidence of substructures (Abell 194; Bird 1994) or not embedded in superclusters (Abell 496; Malumuth et al. 1992) and distant clusters (Cl0939+4713) and regions in the field and in the Coma supercluster.

Since we are studying the galaxy properties along the Hubble sequence and in different environments, we need a catalogue of galaxies formed using selection criteria that do not depend on morphological type and environment. Samples complete in absolute magnitude and volume are representative samples of galaxies. Obviously, with this choice, all galaxies fainter than the absolute magnitude limit are not represented at all, but we are interested only in bright ($M < M^* + 3$) galaxies. Our major concern is not related to rare low surface brightness galaxies missed in most galaxy catalogues, but is related to common, bright galaxies lost because not observed. In our catalogue too, low surface brightness galaxies are missing, but this is because they have fainter absolute magnitudes, and not because we failed to notice them.

Since we are interested in morphology dependent properties, the morphological type is the crucial quantity to be estimated. The observations used to classify the galaxies have to be of good quality, enough to perform the morphological classification, possibly with the same rest frame resolution as that offered by the Hubble Space Telescope for distant clusters. This implies seeing conditions of about 1 arcsec, or better, for Coma galaxies. Furthermore, great attention must be taken in the type determination, in order to limit the scatter of galaxy properties inside each morphological class due just to incorrect type assignment. The type assignment, therefore, has to be:

– independent of galaxy properties other than the ones indicated in the definition of types (based on the geometrical shape of isophotes and on the major/minor axis surface brightness profiles) and

– reproducible, to guarantee the quality of the type assignment and to avoid personal biases.

These prescriptions have been satisfied for the galaxies in the Perseus cluster (whose properties have been presented in Andreon 1994) and in the Coma cluster, whose properties we present in this paper.

2. Why Coma?

The Coma cluster is one of the richer and nearby clusters of galaxies. At first sight, the cluster looks relaxed and virialized in the optical and in the X-ray. It was in fact designated by Sarazin (1986) and Jones & Forman (1984) as the prototype of the relaxed and virialized cluster.

A careful analysis of the spatial distribution of galaxies (Fitchett & Webster 1987, Mellier et al. 1988), good X-ray images (Briel, Henry & Böhringer 1992, White, Briel & Henry 1993), and a large velocity sample (Biviano et al. 1995) revealed some substructures in this cluster. Around NGC 4938, 40 arcmin SW from the cluster center, there is an excess of X-ray luminosity, of galaxies and also of galaxies with a low velocity relative to NGC 4938. Another substructure has been detected deep inside, in the core of the cluster, around one of the two dominant galaxies, NGC 4874, although the situation is complex, due to the fact that, for this structure, the velocity centroid, the spatial centroid and the dominant galaxy are offset with respect to one another. The presence of substructures in Coma has been interpreted as due to the collision of two cluster components, the main body of the Coma cluster and the NGC4839 group, seen just before (Biviano et al. 1995, Colless & Dunn 1996) or just after (Briel, Henry & Böhringer 1992) the first crossing encounter.

The fact that such substructures are common in real clusters (Salvador-Solé, Sanromà & González-Casado 1993; Salvador-Solé, González-Casado & Solanes 1993; Escalera et al. 1994), even in clusters previously considered virialized, again makes the Coma cluster interesting, since its galaxies lived the typical life of galaxies.

For this reason, and taking into account the advantage that many properties of the galaxies in Coma are available in the literature, we focussed our attention on this cluster, studying in particular the variation of galaxy properties along the Hubble sequence from the center to the far outskirts of the cluster.

3. The sample and the physical parameters

In order to avoid the biases arising in a poorly selected sample, we studied a complete flux limited sample formed by all galaxies brighter than B magnitude 16.5 within one degree from the center of the Coma cluster (Fig. 1, upper-left panel, 190 galaxies). At the distance of Coma, one degree corresponds to 2.7 Mpc ($H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$).

The following physical parameters were considered. Positions, B isophotal magnitude, isophotal radius at the 26.5 B magnitude arcsec⁻², often called optical size in the literature,

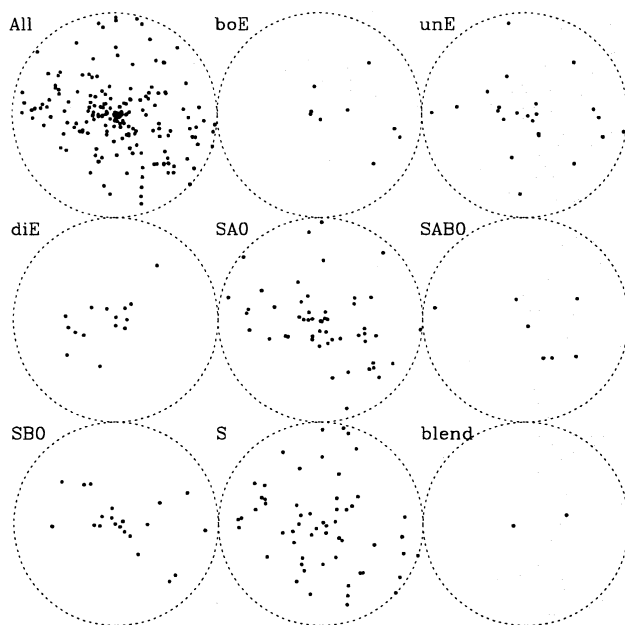


Fig. 1. Spatial distribution of all galaxies of Coma and of each individual Hubble type. North is up and East is left. The x,y coordinate system used in this work is rotated 45 degrees clockwise to align it with the Coma/A1367 supercluster. Note that there are 187 points (galaxies) in the top-left panel. In this small plot some close points are superposed and thus undistinguishable on the diagram.

and the $B - R$ color were taken from Godwin, Metcalfe & Peach (1977, hereafter GMP). Position, B magnitude and radius are known for all galaxies, and $B - R$ color for 92% of them.

Galaxy radial velocities were compiled from a survey of literature data (Kent & Gunn 1982, Caldwell et al. 1993, Biviano et al. 1995 and Colless & Dunn 1996) and of public databases, such as Leda¹ and NED². Radial velocities are known for 91% of the galaxies. For each galaxy, we adopt the median value of the published velocities. Three galaxies of the sample (GMP2796, GMP4366, GMP4592) have a velocity larger than 11000 km/s, and, therefore, they do not belong to the Coma cluster. We discard these three galaxies from our sample.

Ultraviolet (2000 Å) magnitudes were taken from Donas, Milliard & Laget (1995). Their UV flux-limited sample is a 90% complete sample down to UV magnitude 18. Because of the large scatter in galaxy UV-B colors (4 magnitudes), only a small number of galaxies (55) have a UV-B color, but the bias (selection in B) is well known and independent of the morphological type.

Infrared ($J - H$, $H - K$) aperture colors were taken from Recillas-Cruz et al. (1990) who observed galaxies brighter than photographic magnitude 16, as estimated by Dressler (1980a), mostly within 46 arcmin from the center. By selecting galaxies brighter than B magnitude 16 within 46 arcmin of the center, we form a 83% complete and unbiased subsample of 95 galaxies.

¹ Leda is the Lyon-Meudon Extragalactic Database supplied by the LEDA team at the CRAL-Observatoire de Lyon (France)

² NED is the NASA/IPAC extragalactic database, operated for NASA by the Jet Propulsion Laboratory at Caltech.

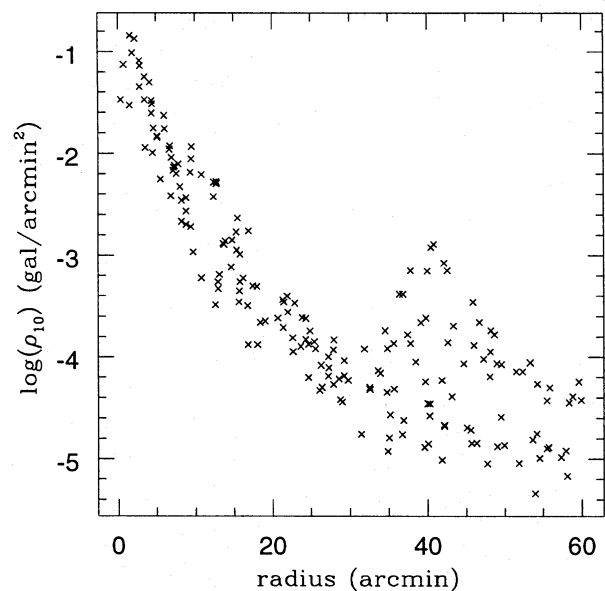


Fig. 2. Relation between the clustercentric distance and the local density in Coma. Each point corresponds to one galaxy.

The morphological types of the galaxies were taken from Andreon et al. (1996) and Andreon et al. (in preparation). These types supersede, or are as good as, the ones from the literature, because of the better resolution of the data used for the classification and because our type are based on the presence of structural components (disk, bar, halo, etc. see Andreon et al. 1996, and Andreon & Davoust, in preparation, for details). For galaxies appearing more than once in these two papers, we adopt the type obtained from the better observational material used. All but 3 blended galaxies are classified in one of the following detailed morphological classes:

boE, unE, diE, SA0, SAB0, SB0, S0/a, S, Irr
where boE and diE stand for boxy and disk ellipticals respectively, and the unE class is a blend of two classes: ellipticals that are not diE and not boE and ellipticals without evidence of boxiness or diskiness. The other types refer to the Hubble classes. As usual, $E = boE + unE + diE$, $S0 = SA0 + SAB0 + SB0$ and early-type galaxies are $Es + S0s$. boEs and unEs were merged in the (bo+un)Es class for physical (Bender et al. 1989) and statistical reasons, whereas the S0/a and the Irr classes were merged with the S class, in the spirit of the Hubble (1926) definition. S0/a are S by definition (see e.g. de Vaucouleurs et al. 1991, p. 15).

The panels of Fig. 1 show the spatial distribution of all the galaxies, for each morphological type, and of the 3 galaxies without detailed type (blended galaxies).

The following quantities are computed for further analysis.

- GMP's x, y positions have been rotated clockwise by 45 degrees (around the cluster center adopted by GMP, $\alpha = 12^h 57^m 18^s$, $\delta = +28^\circ 14' 24''$ (1950.0)) to align the positive x semi-axis with the direction of the NGC4839 group and with the main direction of the Coma/A1367 supercluster;
- the clustercentric distance, the distance to the nearest neighboring galaxy (d_1) and the local density (ρ_{10}), defined as the den-

sity inside the smallest circle containing the 10 nearest galaxies (Dressler 1980a) have been computed. These three quantities are obviously not independent. Fig. 2 shows the tight relation between the clustercentric distance and the local density. The spread at $r \sim 40$ arcmin is due to the NGC4839 substructure.

– the mean surface brightness, $\langle \text{SuBr} \rangle$, has been computed taking into account the galaxy ellipticity.

4. The method

The method used to test the reality of the differences (if any) between the galaxy properties along the Hubble sequence has been presented in Andreon (1994). In summary, the probability that an observed difference is real is computed by Monte Carlo simulations in which the types of the galaxies are shuffled randomly. We did 10^5 simulations for each pair of classes and for each galaxy property analysed. We considered the following statistical quantities: the t value of the T test, the f value of the F test, the tail and skewness indices t_i and s_i , that measure differences between the mean, the dispersion, the kurtosis and the skewness, respectively, of pairs of distributions. We used also the D statistics of the Kolmogorov-Smirnov test, and the P5 probability of the vector (t, f, s_i, t_i, D) . In the determination of the f and t values of the F and T tests, we replaced the mean and the dispersion with equivalent robust quantities, that are less sensitive to outliers. These are the central location index and the scale index (Beers, Flynn & Gebhardt 1990) which, for the sake of clarity, we continue to call mean and dispersion. We verified that our results are insensitive to the choice of the exact form for the mean and dispersion, on the condition that they are robust.

We tested the agreement between the probabilities computed using Monte Carlo simulations and the theoretical ones for the two tests (K-S and classical T tests) for which the theoretical probability function is known, *whatever* the assumed parental distribution from which the data are taken. The comparison concerns real probabilities measured during the statistical analysis and not uniform deviates, as in Andreon (1994). We found an excellent agreement for the T and K-S tests over four decades in probability.

5. Results and comparisons with previous studies

Two degrees of resolution were adopted for the morphological type during the comparison of the galaxy properties: a coarse one (E, S0, S), typical of many works on the morphological segregation of galaxies in clusters, and a finer one ((un+bo)E, diE, SA0, SB0, S).

Fig. 3 summarizes our examination of the morphological dependence of the galaxy properties. Some differences are clearly outstanding, whereas some others are difficult to establish. Table 1 lists the measured probabilities when we found differences larger than “ 3σ ” (or, better, when the probability that the difference is due to random fluctuations is less than 0.002). These graphical and tabular data are discussed in the following sections where we present first our results, then those of the lit-

erature, and discuss both together. Null results are commented only when interesting.

5.1. B Luminosity

Statistically, (un+bo)Es are brighter than all other types, except diEs, which have a similar luminosity function. The bulk of SAOs are fainter than the typical diEs, which have a flatter luminosity distribution. The SA0 luminosity function is marginally narrower than the S one. As a consequence, Es are brighter, on the average, than S0s and Ss.

The shapes of the bright part ($M_B < -19.2$) of the luminosity function of Hubble types are similar to the ones of the field and of the Virgo cluster (Binggeli, Sandage & Tammann 1988) and to the one computed by Thompson & Gregory (1980) for a sample of galaxies of Coma largely overlapping our own, but with fully independent magnitudes (from Godwin & Peach 1977) and (their unpublished) morphologies: the S0 and S luminosity functions increase more sharply than the E one, starting from fainter luminosities. On the contrary, the morphological compositions (i.e. the normalizations of the luminosity function) of the Coma and Virgo clusters differ.

These results support the finding of Binggeli, Sandage & Tammann (1988) that the variation of the bright part of the global luminosity function is related to the variation of the morphological composition and that the luminosity function of each type is universal. However, one exception is known: in the Perseus cluster (morphologies taken from Poulain, Nieto & Davoust 1991 and magnitudes taken from Bucknell, Godwin & Peach 1979) the S0 luminosity function does not differ from the E one (Andreon 1994), as it starts at the same luminosity and flattens off at $M_B \sim -20.5$. Misclassifications between Es and S0s cannot explain the anomaly of Perseus’ S0s, since the rest-frame resolution of the data used to classify the galaxies in Perseus is *better* than the one used for Coma.

The luminosity functions of boEs and diEs of Coma galaxies are compatible, within the large errors due to small statistics, with the ones for Perseus given by Andreon (1994), but both are shifted faintward by one magnitude with respect to the preliminary ones obtained by the ESO-Key Program team “Toward a physical classification of early-type galaxies” (Bender et al. 1993) for a larger and more heterogeneous sample. Photometric (systematic) errors account for a shift of only 0.11 magnitude (necessary to translate our B isophotal magnitude into the asymptotic B magnitude used in the comparison sample). Errors in the morphological classification between the two E classes cannot explain this result, since both classes are affected by the same magnitude shift. This shift must be due to a selection bias, otherwise it would imply that Es, as a whole class, do not have the same luminosity function in different environments, which is in contradiction with observational evidence. It is possible that Bender et al. oversampled the bright end of the boE and diE luminosity functions and that galaxies of normal luminosity are missing, thus explaining the observed result, since their sample is flux limited at a bright apparent magnitude ($B = 13$) but not absolute magnitude complete.

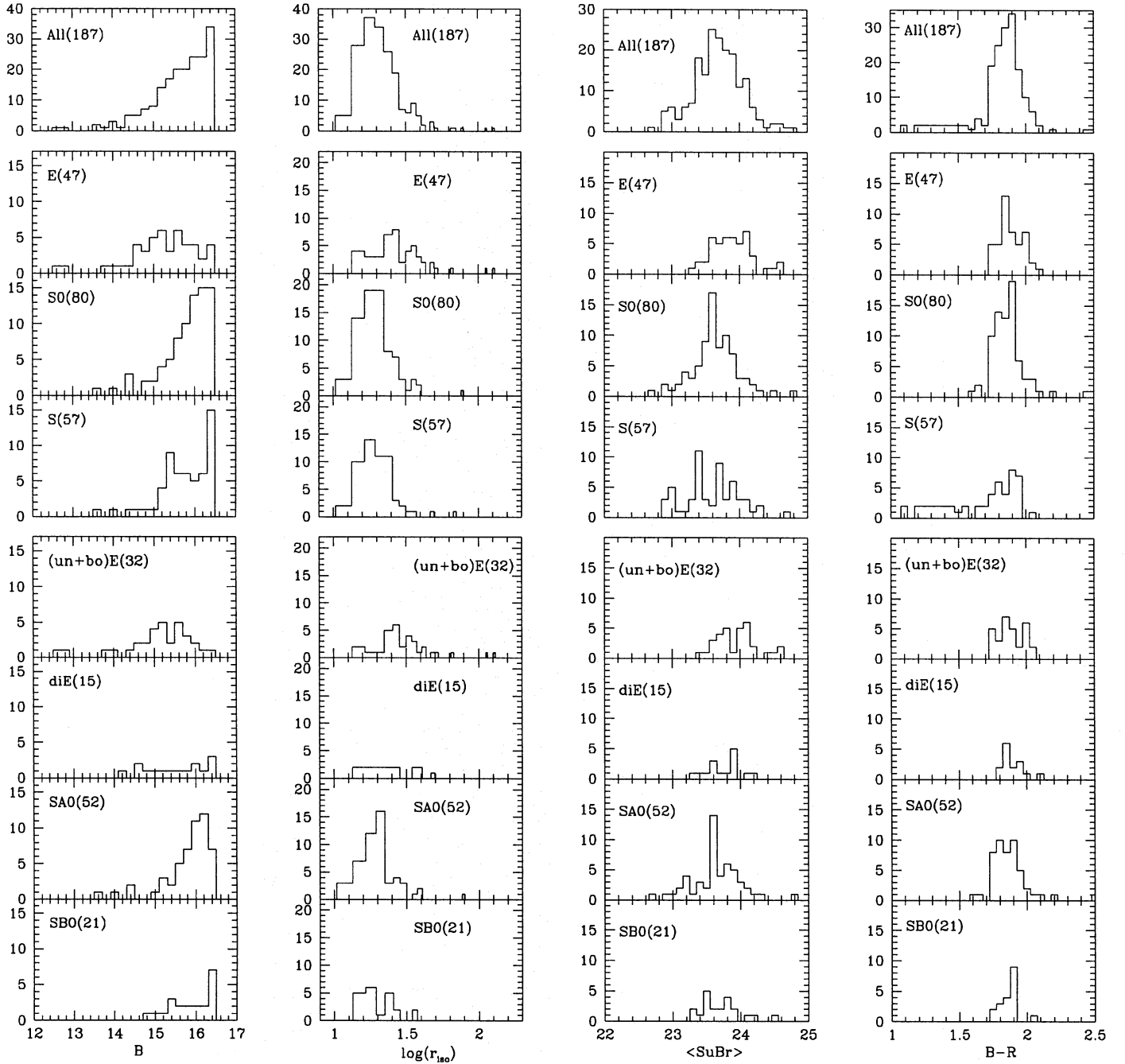


Fig. 3a. Luminosity function, size, mean surface brightness and B-R color distributions of all galaxies of Coma and of each individual Hubble type. Radii are measured in arcsec and surface brightnesses are measured in mag arcsec^{-2}

5.2. Optical size (r_{iso})

(un+bo)Es are larger than all other types but diEs. diEs are a bit larger and their distribution is flatter than later types. Consequently Es are larger than S0s and Ss. The same applies for the coarse classes, Es vs S0s and Ss. However, since Es are brighter and brighter galaxies also have more of everything, our results are dominated by differences in the luminosity functions. We stress therefore that this result, as well as the similar one obtained by Roberts & Haynes (1994), just reflect the luminosity and morphological composition of catalogued galaxies and are

not general properties of the Hubble types. All the other quantities presented in the following are normalized to the galaxy luminosity, and, therefore, the above caveat does not apply.

5.3. Mean surface brightness ($\langle SuBr \rangle$)

(un+bo)Es have a fainter mean surface brightness than all the other classes but diEs. The same applies to the E class compared to S0s and Ss. Therefore, at fixed magnitude, early-type galaxies are larger than other types. Such a difference was not found by Roberts & Haynes (1994) in their sample, either because Coma

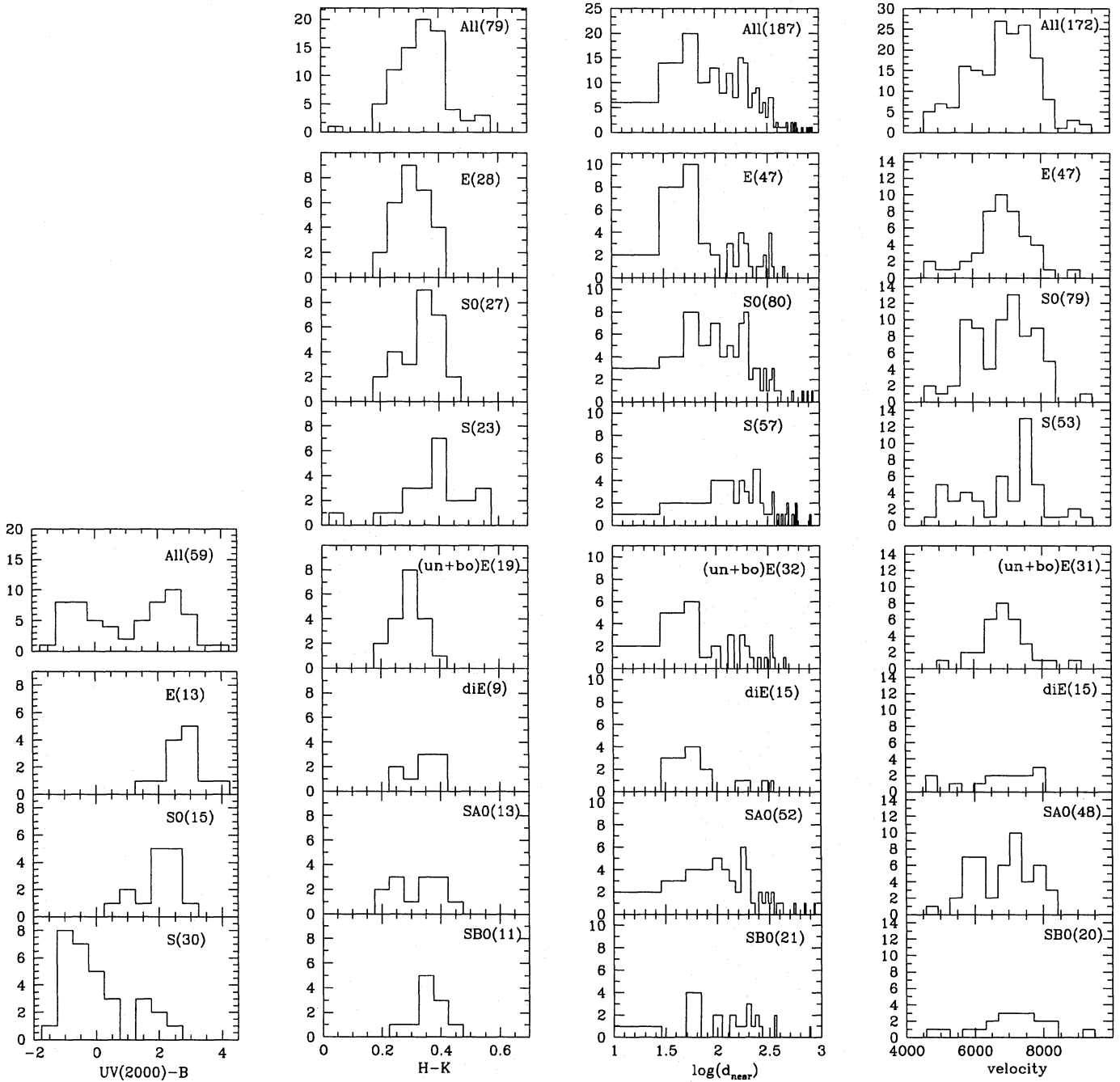


Fig. 3b. Ultraviolet UV(2000)-B and infrared $H - K$ color, distance from the nearest galaxy and velocity distributions of all galaxies of Coma and of each Hubble type. Please note that no correction was applied to raw $H - K$ color. Distances are measured in arcsec and velocities are measured in km s^{-1} . Due to small statistics, the ultraviolet color is shown only for the coarse classes.

galaxies are peculiar or because Roberts & Haynes missed early-type galaxies of mean surface brightness fainter than the typical one of spirals.

Es in Coma are probably not peculiar, since they have the correct dimension for their magnitude, and there is no difference in the fundamental plane for Coma and non-Coma galaxies (Bower, Lucey & Ellis 1992, Guzmán et al. 1992, Jørgensen, Franx & Kjaergaard 1993, Jørgensen, Franx & Kjaergaard 1996).

The dispersions of the E and S0 mean surface brightness distributions are compatible with the ones expected from the 0.13 mag error in the galaxy magnitudes estimated by GMP, and a 13% error in the size measurement, which is a reasonable estimate of that quantity. The width of the S mean surface brightness distribution is larger and must be due to correlations between the mean surface brightness and other galaxy properties, as shown in Sect. 5.10.

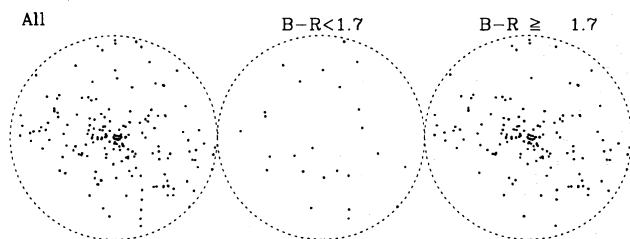


Fig. 4. Spatial distributions of all galaxies of Coma and of red ($B - R \geq 1.7$) and blue ($B - R < 1.7$) galaxies

5.4. $B - R$ color

The color distribution of spiral galaxies markedly differs (as expected) from those of the other coarse and detailed types, because there are no blue ($B - R < 1.6$) early-type galaxies. Es and S0s have the same color (1.87), and no dispersion is present in the two color distributions besides that due to photometric errors. The presence of a bar does not change the $B - R$ color of lenticulars at a statistically significant level. The same applies for the presence of a disk in early-type galaxies. The (un+bo)E and SB0 distributions have opposite skewnesses, but we must be cautious in this case, because we are comparing the shape of two distributions blurred by photometric color errors. Ss have a color distribution which is incompatible with the hypothesis that all Ss have the same $B - R$ color, and, as a result, the spiral color is correlated with the $\langle \text{SuBr} \rangle$ and the galaxy location in the Coma cluster, as shown below.

5.5. $UV-B$ color

Because of the low number of galaxies detected both in B and UV, we only compare the coarse classes. The median colors are 2.92, 2.22, -0.28 for the E, S0 and S classes, respectively, for our B selected sample. We give statistical significance to the finding of Donas, Milliard & Laget (1995) that S galaxies have bluer UV-B color than early-type galaxies (E, S0 and E+S0). The E and S0 color distributions show a dispersion of the same order as the photometric accuracy, whereas the S one has a dispersion twice as large. $UV - B$ is correlated to $B - R$, bluer galaxies being bluer in both colors. The nature of this dispersion is discussed below, together with all the other already mentioned ones.

5.6. $J - H$ & $H - K$ infrared colors

There is no difference between the $J - H$ colors of the detailed and coarse morphological types, showing that the two filters map fundamentally the same luminosity emission. In $H - K$, Es are 0.04 mag bluer than S0s, and 0.09 mag bluer than Ss. A dispersion of 0.07 mag was measured for the E and S0 color distributions, which can be almost completely accounted for by photometric errors, whereas a larger spread is found for Ss (0.12 mag). In $H - K$, (bo+un)Es are bluer than SB0s and Ss, the latter showing also a large range in color.

Infrared colors are not expected to depend on the morphological type in the hypothesis that all emission is due to stars. In

fact, in the JHK bands, the shapes of the spectra of galaxies with very different star formation histories look very similar, except during the first million years for an instantaneous burst (Bruzual & Charlot 1993, their Fig. 4). Therefore we must pay attention to other effects possibly mimicking the detected correlation. Visual inspection of the infrared color magnitude diagrams for each morphological type reveals that the reddest galaxies are Ss, independently of the magnitude, excluding the possibility of a magnitude-color effect.

We looked for confirmation of our finding in the literature for magnitude complete samples. Recillas-Cruz et al. (1990), from which we obtained the infrared colors, did not look for differences in colors between early-type galaxies and Ss. Gavazzi & Trinchieri (1989) observed only spiral galaxies in the Coma supercluster and they found constant infrared colors from Sa to Irr. The situation is actually even more complicated, since the $H - K$ median colors of Gavazzi & Trinchieri's Coma supercluster spirals are similar to those of our Es and, therefore, redder than those of our Ss. Some caution is necessary: Gavazzi & Trinchieri's and Recillas-Cruz et al.'s spirals are not measured within the same aperture, Gavazzi & Trinchieri's sample is not truly complete (and therefore could be biased) and an environmental effect could be present, virtually all of Gavazzi & Trinchieri's galaxies being more than 3 Mpc away from the cluster center and all of ours inside that distance. On the other hand, five galaxies in common between the two samples have equal $H - K$ colors within ~ 0.03 mag and in $J - H$ no differences are found between the two spiral samples. Photometry of a large, complete and more uniform sample of Ss in different environments, through an aperture large enough to encompass any eventual central non stellar emission, is necessary to solve this puzzle.

5.7. Morphological segregations

The diE x-distribution is more centrally concentrated than all the other ones, which are compatible with one another (see also Fig. 1). The SB0 y-distribution is more centrally concentrated than all but the (un+bo)E one. As a result of these two segregations, Es and S0s are more centrally concentrated in the x and the y directions, respectively, than Ss.

Spirals are uniformly distributed over the studied field (see Fig. 1), where the galaxy density varies over four decades, the distance from the cluster center varies from 0 to 2.7 Mpc and the distance to the nearest galaxy from 0 to 600 Kpc.

The nearest galaxy distance of Ss differs from those of the coarse E class and of its two detailed classes. This is in agreement with the findings of studies comparing the correlation function of Ss and Es (e.g. Davis & Geller 1976).

The only, although marginal radial segregation present, concerns diEs, that are spatially more centrally concentrated than Ss.

No statistically significant radial or density segregation is detected; the same result was found for the Perseus cluster (Andreon 1993). As a check, we verified that no statistically significant radial segregation is found for Coma galaxies even us-

Table 1. Probability, expressed in percentage, that two galaxy classes have the same parental luminosity, optical size, mean surface brightness, B-R color, infrared colors, x, y, radial, azimuthal, distance from the nearest galaxy, density and velocity distribution (or, better, one minus the confidence level to reject the hypothesis that the types are drawn from the same parental distribution). Only pairs of morphological types having less than 0.2% of probability to be drawn from the same parental distribution are listed. For the sake of clarity, probabilities larger than 15% are replaced with blanks. Null detections are not listed but are discussed in the text when interesting.

c1	c2	quant.	P5	T	F	SI	TI	KS	c1	c2	quant.	P5	T	F	SI	TI	KS
<i>Detailed morphological classes</i>									<i>Hubble morphological classes</i>								
(un+bo)E SA0 B			0.000	0.000	1.954			0.005	E	S0	B	0.000	0.000	0.436			0.009
(un+bo)E SB0 B			0.001	0.058				0.771	E	S	B	0.006	0.058	13.201			0.090
(un+bo)E S B			0.009	0.054				0.103	E	S0	r_{iso}	0.000	0.000	0.046			0.000
diE SA0 B			0.074	1.099	9.568			13.369	E	S	r_{iso}	0.000	0.000	0.012			0.000
SA0 S B			0.142		3.217				E	S0	<SuBr>	0.000	0.008			4.958	0.223
(un+bo)E SA0 r_{iso}			0.000	0.000	0.519			0.000	E	S	<SuBr>	0.001	0.012	5.426			0.022
(un+bo)E SB0 r_{iso}			0.001	0.009	14.544			0.013	S0	S	<SuBr>	0.156		12.748		10.285	10.141
(un+bo)E S r_{iso}			0.000	0.000	0.851			0.000	E	S	B – R	0.000	0.135	0.168	0.072		0.004
diE SA0 r_{iso}			0.061	0.775	5.366		12.380	11.590	S0	S	B – R	0.000	0.021	0.025	0.729		0.004
diE S r_{iso}			0.034	0.474	2.644			7.233	E	S	H – K	0.000	0.072	0.669		12.444	0.805
(un+bo)E SA0 <SuBr>			0.005	0.015				0.125	S0	S	H – K	0.108	2.754	9.526			4.756
(un+bo)E SB0 <SuBr>			0.164	0.597				2.350	E	S	x	0.115		2.366	2.908	14.701	
(un+bo)E S <SuBr>			0.000	0.007	9.953			0.031	S0	S	y	0.017		2.429		0.130	11.636
(un+bo)E SB0 B – R			0.076		5.288	1.856			E	S	d_1	0.005	0.203				0.054
(un+bo)E S B – R			0.000	2.122	1.085	0.274		0.067	E	S	v	0.059		1.200			12.973
diE S B – R			0.000	12.344	2.857	0.001		0.059	S0	S	v	0.148		3.206			
SA0 S B – R			0.000	1.533	0.270	0.042		0.028									
SB0 S B – R			0.076	13.227	0.453			0.376									
(un+bo)E SB0 H – K			0.083	0.334				1.943									
(un+bo)E S H – K			0.001	0.272	0.584			0.232									
(un+bo)E diE x			0.030	7.205	1.376			13.178	red	blue	<SuBr>	0.000	0.000				0.008
diE SA0 x			0.062		0.703			11.985	red	blue	y	0.125		13.679		3.894	11.641
diE SB0 x			0.141		1.701				red	blue	d_1	0.000	0.119				0.002
diE S x			0.125		0.327				red	blue	ρ_{10}	0.005	0.720	1.981	3.401		0.046
diE SB0 y			0.086	10.451	13.855				red	blue	r	0.039	2.496	0.948			0.112
SA0 SB0 y			0.024		0.850	9.062	10.609		red	blue	v	0.113	3.913	5.782			2.887
SB0 S y			0.000		0.057	2.679	0.548	5.855									
(un+bo)E S d_1			0.097	1.713				0.799									
diE S d_1			0.046	0.396	13.983	8.026		0.365									
diE S r			0.147	0.813	6.752			1.617	red S blue S	ρ_{10}	0.024	0.213	7.256				0.694
(un+bo)E SB0 v			0.040	6.837	13.436	10.661			red S blue S	<SuBr>	0.044	0.234					1.161
(un+bo)E S v			0.013		0.145			8.755	red S blue S	UV-B	0.000	0.121					0.027
SA0 SB0 v			0.174	3.951		6.576											
SA0 S v			0.121		1.317			5.192									

ing Dressler (1980a) morphological types instead of our own, and that our computed densities agree with Dressler's, showing that the lack of detection of the morphology – radius and morphology- density relations is not due to the possibility that our types or densities, respectively, are wrong.

The only statistically significant segregation is with respect to a privileged direction and therefore this is the primary segregation. As stressed in Andreon (1993), this type of segregation naturally implies a radial or density segregation.

Lenticulars are overabundant at all radii and this make the morphology – radius relation not compatible with the standard one presented in Whitmore, Gilmore & Jones (1993).

These two facts suggest that, even if there is a general tendency for galaxies to obey the morphology – density (or radius) relations, evidenced by averaging them over many clusters, as done by almost all previous studies (see references in the introduction), there is a large scatter in the individual clusters

which can affect the morphology-density (or radius) shapes or normalization, as in Coma and in Perseus.

We failed to find a radius or density segregation in the present sample of Coma galaxies, but we did find strong evidence for a different location of the spatial distribution of the types with respect to a privileged direction, the main direction of the supercluster in which they are embedded. The same failure to detect a radius or density morphological segregation and the successful detection of a privileged direction in the cluster also occurred in the case of Perseus, although we did not recognize at the time that the preferred direction was the main supercluster's direction. Many types are concerned, and not only spirals, as expected if the infalling galaxies were mainly spirals and if most of the infall occurred along the supercluster's main direction. Incidentally, the detection of a privileged direction for the spatial distributions of Ss is very difficult from a statistical point of view, because their spatial distribution is fairly uniform over the observed fields. It is normal, therefore, that their spatial distribution looks almost circular in Fig. 1.

We can exclude that the preferred direction that we found is due to biases in the morphological classification, for two reasons. First of all, in our scheme, type assignment does not depend on personal bias; in other words, it is reproducible at more than 95% (Andreon & Davoust, in preparation). Secondly, no personal influence of the author on the type assignment is possible because the type assignment was done before we understood that the preferred direction is the supercluster one, either by people not in contact with author at the time or by two morphologists independently, often not including the author.

We have also verified that the quality of the observations does not depend on the found preferred direction.

5.8. Morphology-velocity segregation

Es and, marginally, S0s have a smaller velocity dispersion than Ss (758, 695 and 1325 km s⁻¹ respectively). The same happens for (un+bo)Es vs Ss and, marginally, for SA0s vs Ss. Blue ($B - R < 1.7$) spirals have a velocity dispersion of 1600 km s⁻¹ whereas red ones have a dispersion of 940 km s⁻¹. The SB0 velocity distribution differs from the (un+bo)E one and, marginally, from that of SA0s, mainly because of a small velocity offset (540 and 380 km s⁻¹ respectively). The qualitative behavior we found for the velocity distribution of the coarse Hubble types is identical to that of the smaller data set of Zabludoff & Franx (1993), but their 2 σ detection of different means is not confirmed using our larger sample and our robust measure of the mean. The spiral velocity distribution is also similar to the ones of Gavazzi (1987) and Donas, Milliard & Laget (1995).

Simple arguments show that the ratio of the velocity dispersion of infalling galaxies to virialized galaxies is $\sqrt{2}$ for an isolated and spherical cluster. This prediction is verified in Virgo (Huchra 1985) assuming that the infalling galaxies are Ss and that the virialized ones are Es and S0s, and in Coma (Colless & Dunn 1996) using the color-magnitude diagram to split the sample into infalling and virialized galaxies. Using

our morphological types, we found that $\sigma_S = \sqrt{3} \times \sigma_E$ and $\sigma_{blueS} = \sqrt{4} \times \sigma_E$.

This means either that the hypothesis of a spherical isolated infall is not verified in Coma, or that infalling galaxies are not only Ss or blue ($B - R < 1.7$) Ss, but even Es and S0s.

5.9. The NGC 4839 substructure

We removed from the sample the 11 galaxies whose distance to the NGC 4839 group is less than ~ 400 Kpc, in order to diminish the effect of this substructure on the galaxy properties. Only negligible changes appear, all of them concern comparisons involving SA0s, which compose the bulk of the flagged galaxies.

If the morphological segregation is universal, then a substructure (a local density enhancement) in a cluster can be detected as a local change of the morphological composition associated with a local density enhancement. Then, the morphological segregation, as the X-ray map, could allow one to disentangle fortuitous alignments (which do not change the local morphological composition) from real density enhancements. We have tested this possibility for the NGC 4839 group. The morphological composition of the clump (E/S0/S=20/60/20) is richer in S0s and poorer in Ss than the mean composition of the cluster at the same radius (E/S0/S=21/33/45), giving a positive result to our test.

5.10. Color dependent segregations

Up to now, we have compared the properties of the galaxies of different types. Since galaxies of different colors in many distant and nearby clusters appear to populate different regions of the cluster (Butcher & Oemler 1984, Schneider, Dressler & Gunn 1986) and to have different properties (Whitmore 1984, Staveley-Smith & Davies 1988), we attempt a comparison of galaxy properties dividing our sample in color bins.

Our statistical tests and inspection of the spatial distribution of red ($B - R > 1.7$) and blue ($B - R < 1.7$) galaxies (Fig. 4) confirm that the color segregation found for many clusters is present in Coma, too. Note that all but one blue galaxy are Ss and that the segregation is present in galaxy density even between red and blue spirals, in spite of smaller statistics. Adding to our sample all blue ($B - R < 1.7$) galaxies brighter than B magnitude 16.5, having a distance from the cluster center between 1° and 1°23', the largest radius contained in GMP's region, confirms the impression that the highest density of blue galaxies is centered at 25 arcmin (1.1 Mpc) from the cluster center and that the density of blue galaxies falls inside and outside this radius. In our sample, $UV - B$ is well correlated to $B - R$, and therefore the bluest galaxies in the optical are also the bluest ones in the UV. It is therefore normal that Donas, Milliard & Laget (1995) detect the largest UV flux density at this radius. We have infrared colors of too few blue galaxies (simply because too few of them have been observed) to say anything about the difference between infrared colors of red and blue spirals, al-

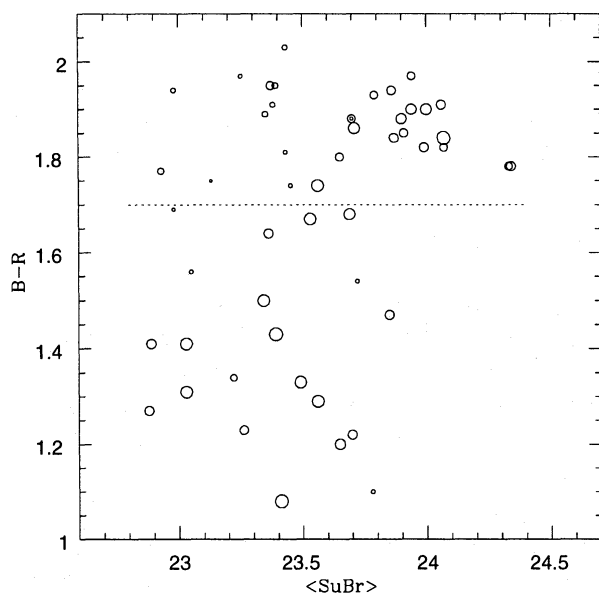


Fig. 5. Optical color vs. mean surface brightness for spirals in Coma (57 galaxies). The dashed line indicates our division of the sample into blue ($B - R < 1.7$) and red spirals. The size of the symbols is proportional to the galaxy ellipticity. Round galaxies are therefore small circles.

though a larger spread than the observational errors was found in the infrared color distribution of spiral galaxies.

The spectra of five of these blue spirals have been observed by Bothun & Dressler (1986). They have “anomalously strong Balmer absorption lines” arising “from a relatively recent star formation event” and the central surface brightness of all three of them (observed in imaging mode) is overbright. Since the UV is sensitive to recent star formation (see e.g. Fig. 4 of Bruzual & Charlot 1993), probably all our blue spirals have experienced an accelerated star formation rate. This is supported by the fact that, in Coma, all blue spiral galaxies, as Bothun & Dressler’s (1986) starburst galaxies, have a higher surface brightness (or are smaller) for their magnitude. In fact blue Ss have a higher mean surface brightness than $23.85 \text{ mag arcsec}^{-2}$ whereas $\sim 50\%$ of red spiral galaxies have a fainter mean surface brightness (Fig. 5). Fig. 5 also shows that red face-on spirals have a higher mean surface brightness than red edge-on galaxies. Geometrical or internal absorption effects cannot account for this behavior, since the observed luminosity of face-on spiral galaxies is fainter, not brighter, than edge-on spirals (see e.g. Boselli & Gavazzi 1994).

In principle, many physical mechanisms can accelerate star formation, as interactions with neighboring galaxies (e.g. Lonsdale, Persson & Matthews 1984) and ram-pressure (e.g. Gunn & Gott 1972). In the first case, blue and red spirals are expected to have different nearest neighbor distributions. Our statistical test fails to reveal such a difference. Even more, we found that bluer spirals have high velocities relative to the cluster center and do not live in low velocity dispersion environments, as expected in this scenario (Bothun & Dressler 1986). In the second case, blue spirals are expected to have higher relative velocities and to be segregated in the intercluster gas-density dimension. Our

statistical tests allow us to detect the first prediction and also to detect a galaxy density segregation (bluer spirals avoid the high densities of the cluster center) that it is an intercluster gas density segregation since gas and galaxy densities are clearly correlated in clusters.

6. The spiral fraction in the Coma cluster

The high spiral fraction we found in the inner region of the Perseus cluster (Andreon 1994), a factor 3 higher than previous determinations, and the systematic underestimate of the spiral fraction in nearby clusters suggested by the redshift dependence of the observed spiral fraction (Andreon 1993), prompted us to compare the spiral fraction of the Coma cluster computed by Butcher & Oemler (1984, hereafter BO) with ours. This comparison is important, since BO’s value of the spiral fraction is the reference for the comparison with distant ($z \sim 0.4$) clusters. The importance of this point is enhanced by the fact that, after the refurbishing of the Hubble Space Telescope, we are now observing distant clusters with better rest-frame resolution than nearby clusters.

Within 22 arcmin from the cluster center, which is the radius within which BO prescribe that the spiral fraction be computed for the Coma cluster, BO found 77 galaxies brighter than B magnitude 16.5. Five of them were classified S by BO and by us, but 14 were classified S0 by BO and S by us. Half of these 14 galaxies were classified S by Dressler (1980a) with an observational material of slightly lower quality than ours, confirming that the estimated spiral fraction of Coma is a lower estimate.

Considering that the median seeing for our data is 1.2 arcsec, whereas an equal rest-frame comparison between Coma and distant ($z \sim 0.4$) clusters requires a 1 arcsec resolution for the whole sample, the spiral fraction in Coma is underestimated by a factor 3, or more, as in Perseus, confirming the tendency of morphologists to underestimate the spiral fraction in nearby clusters, probably because of the low resolution data used.

The spiral excess of galaxies in distant clusters with respect to nearby ones is therefore strongly reduced, although it seems that spiral galaxies in distant clusters do not look like nearby spirals (Dressler et al. 1994), and therefore that a Butcher-Oemler effect, in another form, is still present.

7. The environment and the properties of galaxies

In principle, the environment has two possible effects on galaxy properties. It can limit itself to affecting only the space density of each morphological type. This implies that all galaxies of the same type have the same properties, but different spatial distributions. Or it can affect the internal properties of galaxies (colors, mean surface brightness, shape of the luminosity function, etc.). These two possibilities can be discriminated, since in the first case the internal properties of galaxies are universal, whereas in the second case they depend on the environment.

The results discussed in the previous sections, together with other observational evidence, in particular our results on Perseus

(Andreon 1994), allow us to do such a discrimination. We limit ourselves to present epoch galaxies, leaving the discussion on the variation of the properties with epoch to a future paper.

In the next paragraphs we also show that the coarse morphological appearance of the galaxies (i.e. the E, S0, S Hubble types) splits well the galaxies of different physical types in different classes and brings together similar galaxies of early-type (i.e. Es and S0s), whereas the S class is a blend of galaxies with different properties. Contrary to the case of coarse Hubble types, the detailed morphological appearance of Es and S0s (i.e. the boxiness or diskiness for Es or the presence of a bar for S0s) is not a successful indicator of different internal physical (considered) properties, but it traces well different external properties of the types.

7.1. Es & S0

Early-type galaxies (i.e. not spirals) look *homogeneous* in their internal properties: no difference was found between the properties of galaxies of same coarse morphological type, but of different detailed type. The considered properties are: luminosity function, mean surface brightness, optical and infrared colors. The observed scatter in the properties is the one produced by observational errors. Differences were found between some properties of Es and S0s (the mean surface brightness and the luminosity function). These two facts show that the morphological type is a good way of splitting galaxies of different properties in two classes and of bringing together similar galaxies. The effectiveness of the Hubble morphological scheme for early-type galaxies is a well known fact, for example from the kinematical point of view.

The luminosity function of Es and S0s seems universal: our results for Coma galaxies are fully compatible with the ones for the Virgo cluster and for the field, and, concerning ellipticals, with the ones for the Perseus cluster. The properties of early-type galaxies are not strongly dependent on the distance from the cluster center or the density, otherwise we would detect an inhomogeneity in the properties of these galaxies, and in environments as different as the rich Coma and Perseus clusters, the poor Virgo cluster and the local field. The color-magnitude relation for early type galaxies seems to be universal, independent of cluster richness, X-ray luminosity and redshift up to $z \sim 0.2$ (Garilli et al. 1996). The spectral appearance, and not just the photometric properties, are normal for early-type galaxies in Coma: among the 57 (out of 127) early-type galaxies in our sample selected for spectroscopic study by Caldwell et al. (1993), only a negligible minority (4, i.e. $\sim 7\%$) have an abnormal spectrum (indicative of a starburst). Only slight, if any, systematic departures of the structure and dynamics from the homology have been found for Es when studying the fundamental plane (Pahre, Djorgovski & de Carvalho 1996), perhaps depending on environment (Guzmán et al. 1993) or not (Jørgensen, Franx & Kjaergaard 1993).

All this evidence suggests that Es and S0s are classes of galaxies with homogeneous properties and that the *internal* properties of early-type galaxies are not significantly affected

by the interactions with the galaxy environment, with perhaps one exception (S0s in Perseus).

However, there is evidence that *external* properties of early – type galaxies are affected by the environment. The general tendency for galaxies to obey the morphology – density or morphology-radius relations on the one hand, and the fact that both sub-classes of Es and S0s show differences in their relative spatial distributions in Coma and in Perseus and that their spatial distributions present preferred directions related to the supercluster's direction on the other hand, both point toward a relation between the presence of a galaxy in a determined environment and its morphological type. These two facts are not mutually contradictory: the *space density* of each morphological type in a given environment depends on the environment, but *not the properties* of the morphological types, that depend just on the morphological type and that are the same in all (studied) environments.

7.2. Ss

The situation for spirals looks different. First of all, spiral galaxies are *heterogeneous* in their internal properties: their mean surface brightness and their ultraviolet, optical and infrared colors show a scatter not accounted for by observational errors. Moreover, the optical and ultraviolet colors are correlated with each other and with the mean surface brightness. Bluer spirals are not a random subsample of spirals, in the sense that they have a higher velocity relative to the cluster center, they avoid the high densities of the cluster center and they are overbright for their magnitude.

Therefore, the S class does not regroup similar galaxies, but it is rather a blend of classes of galaxies with different properties. The scatter in the internal properties is intrinsic, at all spiral stages as even incomplete samples show (for optical color, see Gavazzi & Trinchieri 1989; for mean surface brightness, see Roberts & Haynes 1994; for many properties of Sb and Sc galaxies, see Staveley-Smith & Davies 1987 and 1988) and therefore the scatter we found in the coarse S class does not come from our coarse sampling of the spiral stages. This conclusion is reinforced by the fact that the variation of the properties along the spiral stages is small or absent (e.g. Gavazzi & Trinchieri 1989 for infrared colors).

Once we have established that the observed spread in the galaxy properties is not due to our coarse sampling of the S class and that splitting Ss in traditional stages does not improve the situation, our next step is to determine the appropriate binning of the S class that will bring together similar galaxies and put in different stages galaxies with different properties. This will give us a reason for the heterogeneity of the S class. Optical (or ultraviolet) colors are a definite possibility. Using this parameter to discriminate between Ss of different “stages”, we find that bluer, and therefore strongly star forming, galaxies are much more segregated and have a larger velocity dispersion and higher brightness than redder spiral galaxies. This means that the internal galaxy properties are correlated with the properties of the environment, immediately suggesting an environmental

effect. Such an effect has already been detected as a (not statistically significant) difference in the luminosity function of S in high density vs low density regions (Dressler 1980b) and in clusters vs the field (Binggeli, Sandage & Tammann 1988).

With respect to early-type galaxies, whose space density (but not their properties) is determined by the environment, the situation is the opposite. The spiral spatial distribution is uniform in the field of Coma (this work) and in that of Perseus (Andreon 1993) and, therefore, the spiral space density is independent of the galaxy density (and of related quantities, such as distance from the cluster center and intergalactic gas density). All the internal properties of spirals measured with sufficient statistics show a trend with galaxy location. We remind the reader that a uniform spiral distribution gives a spiral fraction rising with distance from the cluster center (or increasing as the density decreases).

The star formation induced by ram pressure naturally accounts for the found segregation of blue spirals, for their higher mean surface brightnesses, larger relative velocity with respect to the cluster center, bluer color in optical and in ultraviolet. The same mechanism has no effect on Es and S0s galaxies, since these galaxies are gas poor, naturally accounting for the fact that the internal properties of Es and S0s are environment independent.

7.3. The re-interpretation of the observed morphological segregation

The observed morphological segregation is the composition of two opposite effects: the dependence of the Es and S0s density on the whole galaxy density (and related quantities) and independence of the space density of Ss from the whole galaxy density. These two effects produce the known morphology-density or morphology-radius relations. There is a large scatter in both relations, so large that we did not detect them in Perseus and Coma.

The fundamental parameter that determines the segregation is not the distance from the cluster center, as claimed by Whitmore, nor the galaxy density, as first claimed by Dressler, although the two exist, i.e. if you have enough statistics and you look for a dependence on one of these two parameters you find the segregation that you are looking for, as firstly shown by Sanromà & Salvador-Solé (1990). The fundamental parameter is not yet determined, but it is certainly related to the supercluster's main direction. In fact, early-type galaxies are segregated in a way related to the main direction of the supercluster in which they are embedded.

The usual detection of a radial (or density) relation presented in literature probably arises from the azimuthal average implicitly done by previous authors in studying the superposition of many different clusters whose supercluster directions are (obviously) not aligned and/or in studying only the radial dependency of the morphological segregation.

The stronger effect of the environment on galaxy properties, the color dependence of spiral galaxies, i.e. their star forming

rates, fails to be found by the standard morphological segregation which is related to changes in the galaxy morphological type. A consequence is that spiral colors, i.e. their star formation rate, is more sensitive to the environment than Hubble type, and it is this quantity that we have to investigate in order to study the effect of the environment on galaxy properties.

7.4. The dichotomy of boEs and diE

Starting with Bender et al. (1989), many authors have claimed there are differences in the properties (luminosity function, radio to optical luminosity, galaxy location with respect to the cluster center ...) between small samples of boE with respect to even smaller samples of diEs (e.g. Longo et al. 1989, Shioya & Taniguchi 1993, Caon & Einasto 1995). An effort to enlarge the sample of galaxies, observing as many galaxies as possible *known* to be ellipticals, has been done by Nieto et al. (1991), Poulain, Nieto & Davoust (1992), and by the ESO-Key program "Toward a physical classification of early-type galaxies" (Bender et al. 1992).

Because of the existence of ellipticals not catalogued as such or not catalogued at all, we follow another approach, more expensive from the observational point of view, with the aim of not missing any elliptical. We start to observe *complete* sample of galaxies, regardless of their morphological type. We think that the comparison of the results obtained on perhaps large but not fully controlled samples with those on smaller but well controlled samples could give some insights on the reality of the differences found (if any) between the properties of diE and boE.

Complete samples fail to show differences between (bo+un)E and diE. In Coma, diEs are less spatially dispersed in the direction of the supercluster than other types, including (bo+un)E. Beside this, diEs and (bo+un)Es share the same properties (luminosity function, optical size, mean surface brightness, optical and infrared colors, radial, density and nearest galaxy distributions), within the large statistical errors due to the small statistics. In Perseus, (bo+un)E and diE share the same luminosity function and their spatial distribution presents a privileged direction, as in Coma. diE are more frequent than boE (+Epec) in two clusters studied with magnitude limited complete samples (14 vs 2 in Perseus and 15 vs 9 in Coma), but many galaxies are unclassified ellipticals (13 in Perseus and 11 in Coma), because of the larger distance of these two clusters compared to Virgo and the local field, and because of the existence of ellipticals which certainly are not diE and not boE. boE and diE in clusters share also the same radio-emission properties (Ledlow & Owen 1995).

On the contrary, in incomplete samples, often of the same size or smaller than our complete samples, one finds differences between boE and diE. Bender et al. (1989) find that radio-loud galaxies are preferably boxy ellipticals, Shioya & Taniguchi (1993) find a larger frequency of boE in clusters, basing themselves on the incomplete and biased sample of Bender et al. (1989), rich in boxy radio-loud galaxies. Caon & Einasto (1995)

find that, in Virgo, boE are found in higher local galaxy density regions than diE.

The two approaches thus lead to opposite conclusions on luminosity function, frequency, distance from the cluster center, local density and on the radio to optical luminosity of boE and diE. We think that the best conclusion we can draw is that differences, if any, between the properties of boE and diE are subtle and that the present samples are too small or too biased to enable one to detect them.

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