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The morphology-density relationship for clusters of galaxies revisited

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Abstract. Back in 1990 Schombert and West (ApJ 363, 331) reported the discovery of a morphology-density relation for clusters of galaxies analogous to the well established dependence of galaxy types on local galaxy density. Based on a sample of 206 Abell clusters they concluded that Rood-Sastry (RS) C and I types (round and irregular) were much more prevalent in low-density regions while L and F (linear and flattened) occurred predominantly in rich supercluster environments; they did not find any similar correlation either for RS cD and B types or for Bautz-Morgan types. Using a much more extended sample (541 Abell clusters) we show that there is no evidence of SW's claimed correlation so that, on the basis of our analysis, we can conclude that the shape of clusters of galaxies is not determined by the local large-scale structure.

Key words: galaxies: clusters – large scale structure of the Universe

1. Introduction

The study of the relationship between the morphology of (extra)galactic systems and their environment is one first and very important step in the path of understanding the clues to the origin and evolution of this morphology and of the systems themselves. Concerning galaxies, the relationship between morphology and environment has become a very well established fact and a cornerstone of our knowledge of galaxies and clusters. Hubble & Humason (1931) first showed that the relative proportions of different morphological types were different in clusters and in the field and later on Oemler (1974) evidenced this very same fact among clusters of different richness. Dressler's (1980) seminal work went a step forward: it established a very well defined relationship betwen morphological fractions and local projected number density. The interpretation of this observational evidence (i.e. how morphology correlates with true local number density) is not without some controversy (see for instance Salvador-Solé et al. 1989) but in any case it is one major fact to be taken into account for any theory of large-scale formation. Later on (Bhavsar 1981, de Souza et al. 1982, Postman & Geller 1984) it was shown that this relationship holds for a wide variety of density ranges from loose to compact groups. All in all these observational facts are central points in the ongoing nature versus nurture debate, as far as galactic morphology is concerned.

The relationship between the morphology of clusters of galaxies and its environment is not so well established and the very same definition of morphology has much to do with this fact. Galactic morphology is, since Hubble and de Vaucouleurs, a very well established parameter for galaxies and it is inextricably tied to the very existence of galaxies themselves. This is not so for clusters of galaxies. Though the existence and significance of clusters themselves is out of the question, its identity as different from the groups and/or the supercluster environment, is a matter of ongoing investigation (see for instance Andersen & Owen 1994). Therefore it is not surprising that the morphological classification of clusters does not have a Hubble-like scheme. Abell's (1958) first taxonomical classification of clusters into regular and irregular was followed by Zwicky et al.'s (1961) dividing clusters into compact, medium compact and open. But two more elaborate schemes are those which have survived as far as cluster morphological classification is concerned: Bautz & Morgan (BM) (1970) and Rood & Sastry (RS)(1971)

RS's scheme is based on the projected distribution of the brightest galaxies in the cluster. Six types, cD, B, C, L, F and I are interpreted as corresponding to a sequence of cluster evolution (Struble & Rood 1982, 1984). cD and B types would correspond to the more evolved stages, with giant galaxies in the center of the cluster as a final product of mergers. C and L types would correspond to regular structures appearing in the process of dynamical evolution, while F and I types, with more amorphous appearance and the presence of many substructures, would correspond to the early stages of the cluster formation. Struble & Rood (1982,1984) have pointed out several difficulties in telling one class from the others though finally they argue that a level of confidence of 90% can be assigned to all currently available RS classifications.

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BM's classification is not exactly a morphological one, in the sense that clusters are not classified by their overall appearance but by the dominance of the brightest cluster galaxy in size and luminosity with respect to the other galaxies in the cluster. Bearing this in mind, BM type might not be a good parameter to estimate morphology; indeed, Bothun & Schombert (1990) showed that there is no strong correlation between the dynamical state of brightest cluster galaxies and the overall cluster properties.

In a pioneering paper, Schombert & West (1990) (hereafter SW) studied the possible relationship between cluster morphological types and local cluster density, in much the same spirit as Dressler's (1980) study on galaxies inside clusters. They did not find (as they themselves expected) any correlation when using BM types but did find a correlation that might be significant when RS types were used as morphological parameters. This correlation was in the sense one would expect if cluster morphology was influenced by the supracluster environment: clusters with flattened structure (RS types L and F) were found more often in regions of higher cluster density, while rounder or amorphous clusters (RS types C and I) were more prevalent in low-density environments. Therefore, SW's result has become an important observational reference in our knowledge of clusters of galaxies: it argues in favour of the physical significance of RS classification and at the same time it constitutes an observational constraint for cluster formation theories.

Given the importance of SW's results, that they were extracted from a sample of 205 clusters (all that was possible back in 1990) and that relevant data for this analysis has nearly doubled since then, we have considered it worthwhile to re-examine SW´s result. This is the aim of this paper which is organized as follows. In Sect. 2 we describe the data sample used. In Sect. 3 we re-examine, in much the same manner as SW's original work, the new data sample. Finally in Sect. 4 we discuss the new results.

2. Cluster sample

As in the original SW study, our sample of clusters is extracted from the catalog of Abell, Corwin and Olowin (1989) (ACO). For a study like the one we are aiming at, the two basic parameters needed are the measured redshift and the morphological classification. As of 1990 nearly 700 ACO clusters had both parameters known, mainly extracted from the Struble & Rood (1987) list and also those published by Rhee & Katgert (1988a,b) and Kirshner et al (1987). Today this figure has nearly doubled, mostly due to the work of Huchra et al. (1990), Andernach (1991), Postman et al. (1992), Zabludoff et al. (1993), Dalton et al. (1995) and Quintana & Ramirez (1995). Taking together all the published data we have a compilation of 1371 ACO clusters having both redshift and morphologycal type (RS and/or BM) known.

To evaluate the local density associated to each cluster we need to determine the distance of each cluster and the number of neighbour clusters within a certain distance. Since the aim of this paper is to check out whether the claimed (SW's) correlation

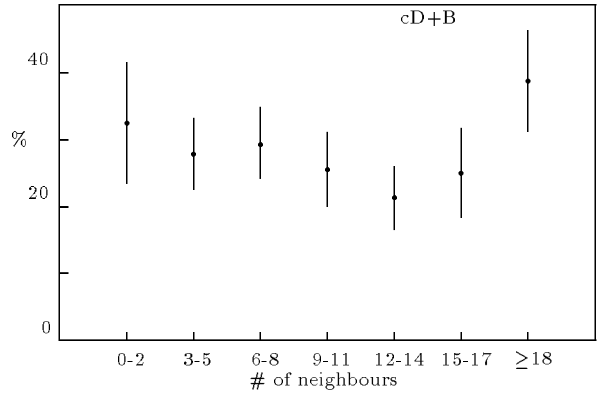

Fig. 1. Percentage of Rood-Sastry cD+B types as a function of the local density of neigbouring clusters.

is confirmed or otherwise fades out in the light of new data, we have computed both parameters in the same way as the original SW work. Thus distances were computed assuming $q_0 = 0$ and a pure Hubble flow,

$$D = \frac{cz(1+\frac{z}{2})}{H_0(1+z)^2}$$

(Weinberg 1972), assuming $H_0 \equiv 100 h \mathrm{kms}^{-1} \mathrm{Mpc}^{-1}$.

For the local density we also used N_{50}, i.e. , for each cluster the number of neighbouring clusters within a sphere of radius $r = 50Mpc$ centered on it. For this purpose we have used all ACO clusters having measured redshifts.

At this point each cluster with known morphology has its associated local density parameter (N_{50}) and we must screen out these data so as to get an homogeneous sample. First of all, to minimize the effects of incompleteness at low Galactic latitudes we will eliminate those clusters with Galactic latitude $|b| < 30$. Secondly, we must take into account the effects of incompleteness.

Though the data sample is a rather heterogeneous one (see SW for a thorough discussion of this fact), for the sake of comparison we must basically take into account the incompleteness that is expected at high redshifts.

Indeed, in Table 1 we list the average number of neighbouring clusters as a function of redshift and how they distribute in richness classes (0 to 5). For all clusters in every redshift bin we have calculated the mean value of N_{50}, $< N_{50} >$; N is the total number of clusters in each bin, which distribute according to the different richness classes. As we can see there are scarcely $R \geq 4$ clusters and very few of them are $R > 1$.

In Table 2, where we list $< N_{50} >$ for every richness class in the sample, we see that there is no definite trend of this parameter with richness, so that the only effect we must take into account is the incompleteness in the redshift sample. Since there is no abrupt drop of $< N_{50} >$ up to redshifts of about 0.13, we shall keep in our sample all clusters with $z \leq 0.13$ (as compared with $z \leq 0.08$ in SW). This leaves us with a final sample of 541 clusters, all of which have RS classification and 440 of them also have BM types. This is to be compared with SW's sample

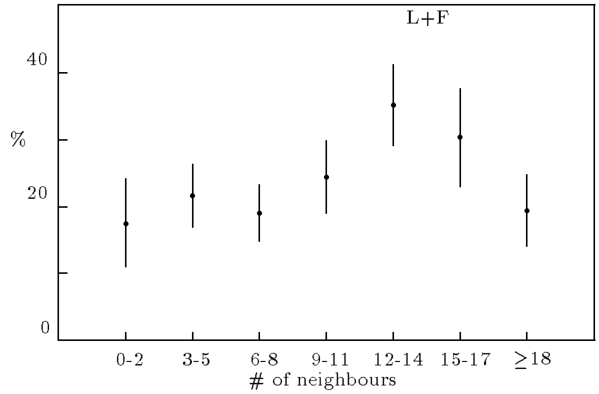

Fig. 2. The same as Fig. 1, but for Rood-Sastry L+F types.

Table 1. Average N_{50} as a function of redshift and richness

z	$< N_{50} >$	N	0	1	2	3	4	5
0.00-0.04..	11.59	39	20	15	4	0	0	0
0.04-0.05..	13.43	30	14	15	1	0	0	0
0.05-0.06..	13.98	56	29	26	1	0	0	0
0.06-0.07..	12.70	60	29	25	4	2	0	0
0.07-0.08..	9.65	88	33	43	11	1	0	0
0.08-0.09..	9.23	67	22	36	9	0	0	0
0.09-0.10..	6.77	39	13	22	3	1	0	0
0.10-0.11..	8.53	47	14	21	8	4	0	0
0.11-0.12..	9.44	70	18	36	16	0	0	0
0.12-0.13..	9.13	45	13	17	11	4	0	0
0.13-0.14..	5.46	54	10	27	13	4	0	0
0.14-0.15..	4.00	31	5	15	7	3	1	0
$>$ 0.15.....	2.50	259	27	97	85	43	6	1

Table 2. Average N_{50} as a function of richness class

R	$< N_{50} >$	N
0	11.00	205
1	10.39	256
2	8.44	68
3	9.50	12
4	—	0
5	—	0

of 206 clusters (all with RS classification) and 175 with BM types. Therefore, while the total number of ACO clusters with published redshift has roughly doubled since the original SW paper, the useful sample has gone up by a factor greater than that. This allows a more statistically significant analysis to be performed.

3. Analysis

In order to be able to compare our results with those obtained by SW we have grouped the RS types into three classes, namely cD+B, L+F, C+I. As for BM types we have grouped them into three classes: I+I-II, II+II-III and III

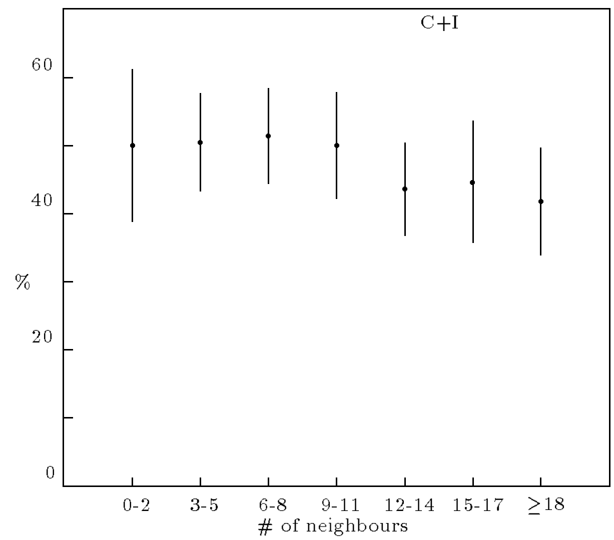

Fig. 3. The same as Fig. 1, but for Rood-Sastry C+I types.

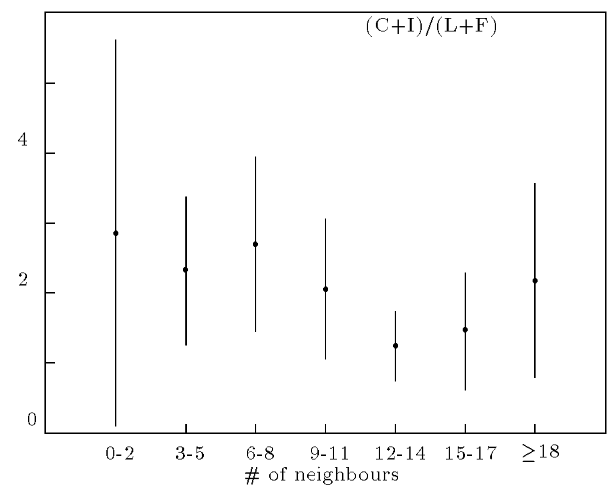

Fig. 4. Ratio C+I/L+F as a function of the local density of neigbouring clusters.

In Table 3 we show the distribution of the different morphological types as a function of N_{50}: for each density bin we have calculated the percentage of the total population (we give the corresponding total number in parentheses). In Figs. 1 to 3 we plot these results for RS types, while in Figs. 5 to 7 we do the same for BM types. Error bars are $N^{\frac{1}{2}}$ counting statistics.

One first look at any of these figures shows us that there is no evident trend of any correlation between percentage and density in any of them. These figures are constructed in the same way as Figs. 1 to 4 in SW paper. There, it appeared that a clear trend was present for RS types, with L+F types steadily increasing with local density and C+I types decreasing in high density regions; in fact this trend was not so obvious for C and I types separately (SW's Fig. 2) and did show up more clearly when both types were combined and compared (C+I/L+F) with more evolved types (SW's Fig. 3). We have performed the same analysis (our

Table 3. Morphological types as a function of N_{50}

	No. of neighbours						
Cluster type	0-2	3-5	6-8	9-11	12-14	15-17	$\geq$ 18
			Types R-S				
cD+B....	31 (13)	28 (27)	29 (31)	26 (21)	22 (20)	25 (14)	39 (26)
L+F.......	18 (7)	21 (21)	19 (20)	24 (20)	35 (33)	30 (17)	19 (13)
C...........	23 (9)	28 (27)	23 (24)	16 (13)	20 (19)	22 (12)	20 (13)
I............	28 (11)	23 (22)	29 (30)	34 (28)	24 (22)	23 (13)	22 (15)
			Types B-M				
I+ I-II....	13 (4)	15 (12)	22 (21)	22 (13)	12 (9)	16 (7)	21 (10)
II+II-III.	55 (17)	54 (45)	42 (40)	43 (26)	49 (39)	42 (19)	45 (21)
III..........	32 (10)	31 (26)	36 (34)	35 (21)	39 (31)	42 (19)	34 (16)

Table 4. Spearman rank correlation

Type	cD+B	L+F	C+I	C	I	I+I-II	II+II-III	III
r	-0.178	0.535	-0.714	-0.642	-0.428	0.178	-0357	0.571

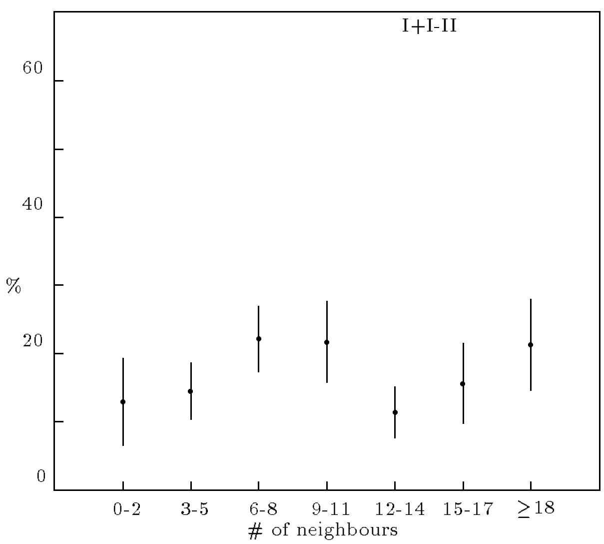

Fig. 5. The same as Fig. 1, but for Bautz-Morgan I+I-II types.

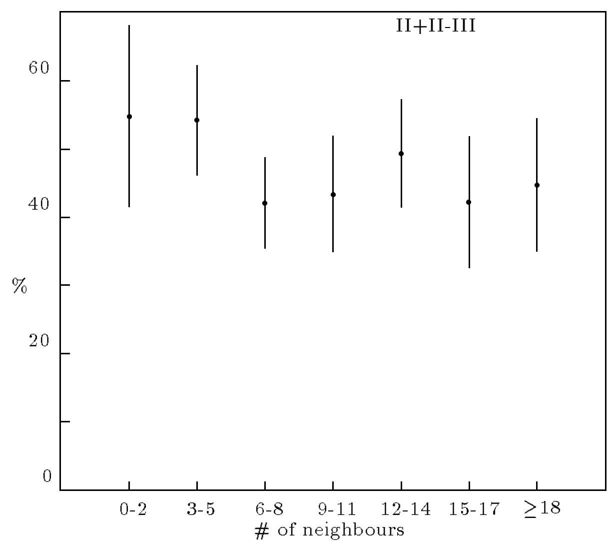

Fig. 6. The same as Fig. 1, but for Bautz-Morgan II+II-III types.

Fig. 4). In fact our figures are not directly comparable with those in SW: our three higher density bins should be lumped together in order to do so. But the point is that with a larger sample the trends (if any) become clearly weaker so that the claimed correlation fades out.

Two points must be stressed before performing a statistical analysis of our data to confirm this lack of correlation. First of all our biggest sample allows us to broaden our range of density bins. Secondly it must be stressed that in SW's figures one density bin (one out of five) was determinant as far as the appearance of correlation is concerned (and, as we shall see, this is also determinant in the type of non-parametric statistical test that one can apply to this kind of data sets). For instance, SW's Fig. 1 shows a similar trend (increasing percentage with increasing density) for both cD+B and L+F types except for the second bin in the cD+B case; this determines the difference in the result where a correlation is claimed for the L+F type but not for the cD+B type. On the other hand, in SW's Fig. 3 (C+I type) the percentage decreases with increasing density, but for the second bin; but now the chosen statistical test yields a significant correlation.

To test the statistical significance of any possible correlation we use the Spearman rank correlation test, a non-parametric test which contrasts the null hypothesis of lack of correlation between two random variables X and Y. From them we shall have a random sample of size n, (x_i, y_i), and we order separately the random samples x_i and y_i in order of their increasing values: then each value is assigned a rank (or number of order) $R_i(x)$ and $R_i(y)$ and we calculate the differences $d_i = R_i(x) - R_i(y)$. It can be demonstrated that the estimator

$$r = 1 - 6 \sum_{i=1}^{n} \frac{d_i^2}{n^3 - n}$$

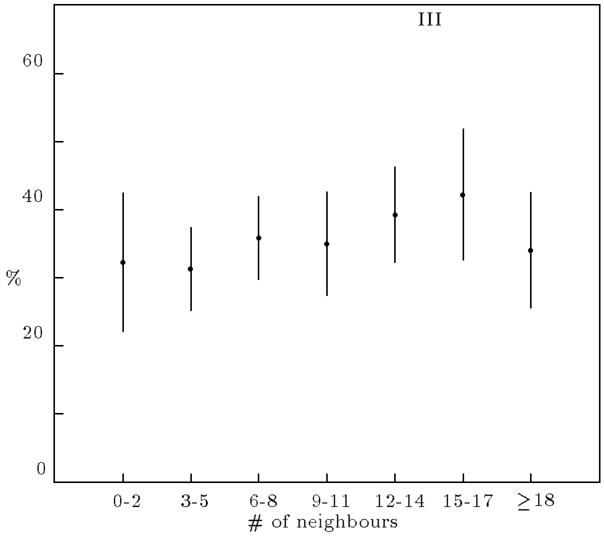

Fig. 7. The same as Fig. 1, but for Bautz-Morgan III types.

has zero mean under the null hypothesis (no correlation). We shall reject this hypothesis (i.e. we shall admit the alternative hypothesis that there exists some correlation between X and Y) if $|r| > r_\alpha$, where r_α is a value which depends on the level of confidence α and is tabulated for different α's and sample sizes (see for instance Snedecor & Cochran 1967)

In Table 4 we list the values obtained for r corresponding to the different morphological types. Since the value of r_α for a sample of n=7 and a confidence level of 95% (99%) is 0.750 (0.893) we conclude with statistical significance what was already apparent from the figures: no correlation is observed between any morphological type and local cluster density.

4. Discussion

The effect of environment on the morphology of clusters of galaxies, basically as far as their overall shape is concerned, has been dealt with by many authors during the last decade: many observational, theoretical and N-body simulation efforts have been dedicated to ascertain whether this effect exists at all, what this tells us about the origin and evolution of clusters and what their cosmological implications are. Debate and controversy on this topic are still alive.

From the observational point of view it has long been claimed (Binggeli 1982, Flin 1987, Rhee & Katgert 1988a, West 1989, Plionis 1994) that clusters of galaxies tend to be aligned with their neighbouring structures, though this observational result has not been found by other authors (Struble & Peebles 1985; Ulmer et al. 1989; Fong et al. 1990; Martin et al. 1995). Theoretical studies have demonstrated that environment could play a determinant role on the shape of clusters. Binney & Silk (1979) claimed that the elongation of clusters could be originated by tidal distortion by neighbouring protoclusters. Salvador-Solé & Solanes (1993) also demonstrated that nearest neighbouring clusters can cause tidal distortions that could account for the observed shapes of clusters of galaxies (Plionis et al. 1991, de Theije et al. 1995). Also shear fields due to the surrounding mass distribution could have an influence in this shape (Bertschinger & Jain 1994, van de Weygaert & Babul 1994). On the other hand, in a top-down scenario, where clusters fragment out of larger structures, this very same fragmentation would imply that clusters could be aligned in the direction of the original sheets or pancakes (Zeldovich 1978). As for N-body simulations, their results have also been controversial, if not contradictory. Dekel et al. (1984) showed that the existence of alignments would favour the top-down scenario, while more recent results (West et al. 1989, West et al. 1991) do not rule out a hierarchical scenario but point out that the influence of environment in the morphology of clusters is a powerful constraint for models of structure formation; it could also give us information about the density parameter Ω, as shown by Evrard et al. (1993)

Schombert and West's (SW) approach and finding of a morphology-density relationship for clusters of galaxies supported the additional claimed evidence of clusters alignments with neigbouring structures. It must be pointed out that due to the small sample used (206 cluster) these authors found a marginally significant correlation and it was argued that a larger and more homogeneous sample of clusters might produce a statistically significant correlation. However, our results, using the same approach as SW and a much more extended sample, show that there is no evidence of this morphology density relationship. In this sense our result would tend to align with those who do not find any significant trace of alignments between clusters and their neighbouring structures, as most recent and systematic studies seem to indicate (see Martin et al. 1995).

Morphology of clusters of galaxies, as established by both RS and BM classification systems, is a rather qualitative parameter, certainly much more so than the Hubble scheme for galaxies. In this sense it would be interesting to find a more quantitative measure of morphology for clusters: Buote & Tsai (1996) have proposed such a scheme, based on X-ray observations of clusters and have applied it to dynamical studies of clusters. Unfortunately not enough data are available yet to apply them to a systematic study of morphology versus environment. Obviously one could argue that possible sources of error (morphological mis-classification, contamination, uncompleteness at high redshift) could conspire to hide out an existing correlation. However, after a detailed analysis of the best available data the null hypotesis must be kept: in the light of currently available data and morphological classification systems for clusters of galaxies there is no evidence that the shape of clusters of galaxies is strongly influenced by the local large-scale structure.

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