

Structure and kinematics of galaxy clusters

II. Substructures and luminosity segregation

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Abstract. A homogeneous sample of galaxy redshifts in the core regions ($R \leq 0.5 \text{ h}^{-1} \text{ Mpc}$) of 12 clusters is used to measure the frequency of substructure with different tests. In 50% of the cases substructure is detected, a frequency which agrees well with previous studies of cluster cores. Magnitude information and rough morphological classes are also available for 80% of the sample, allowing us to confirm that bright galaxies ($M \lesssim -22^{mag}$) have a significantly lower velocity dispersion than the rest. Elliptical galaxies are the main responsables for this luminosity segregation in velocity space, whereas no segregation can be seen for spiral galaxies. Given the coincidence of substructure and luminosity segregation, a cluster model with an old population of ellipticals which are under the effect of dynamical friction in each subcluster is thus favoured by these observations. Spiral galaxies seem to be late arrivals, or are passing in front or behind the core of the cluster.

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

1. Introduction

One of the main results of recent galaxy cluster research is the unambiguous finding that these high-density structures are still continuing to be built or at least significantly reshaped. Undoubtedly, the discovery of substructures has played an important role, changing our understanding about the degree of dynamical evolution in galaxy clusters.

Several statistical treatments to measure the frequency of substructures have been presented during the last decade. Nevertheless, the question about the significance of substructure detections on small scales or in the *core* regions of clusters has been touched only in a few works (Fitchett & Webster 1987; Mellier et al. 1988; Escalera et al. 1992; Salvador–Solé et al. 1993).

It is interesting that the frequency and degree of clumpiness in the centers of clusters could be helpful in establishing the

density profile of dark matter, and even allow an estimation of Ω (e.g. Richstone et al. 1992). If namely dark matter was strongly concentrated towards the cluster center one would expect tidal forces acting towards the disruption of subclumps (see González-Casado et al. 1994 for a discussion).

Examining the very centers of galaxy clusters is rewarding for another reason. The importance of accretion or “cannibalism” (Ostriker & Hausman 1977) during the formation of a cluster is not well established, because right in the cores of galaxy clusters the galaxy velocity dispersion is expected to be too high to allow an efficient dynamical friction (Merrifield & Kent 1989, Gebhardt & Beers 1991, Blakeslee & Tonry 1992). An attractive solution to this problem has been proposed by Merritt (1985). As also numerical simulations suggest (West & Richstone 1988, Serna et al. 1994), dynamical friction could be an important mechanism during the evolution of galaxy clusters. If this is the case, it should be possible to detect signs of equipartition of kinetic energies for the most massive galaxies in dense regions, leading to a correlation of velocity dispersion with galaxy luminosity. Early observational studies of mass segregation were mostly limited to the positions of galaxies in projection, with the exception of e.g. Chincarini & Rood (1977), and no general agreement was found about the relevance of luminosity segregation in velocity space. Recently, Biviano et al. (1992) once again stated the evidence for mass segregation in the *velocity distribution* of a merged cluster sample taken from the literature. Presumably, the phenomenon is easily overlooked in individual clusters studies because of the limited number of galaxies involved.

On the other side, a difference in the kinematic properties between early and late-type galaxies has also been detected (Binggeli et al. 1987, Sodr e et al. 1989). This means that one should look separately at early and late-type galaxies, because galaxies which didn't take part in most of the cluster evolution are not expected to show signs of mass segregation.

This paper addresses the problem of mass segregation and central substructure based on a homogeneous sample of kinematical data (Stein 1996, hereafter Paper I). It is organized as follows: Sect. 2 gives a description of the data used, i.e. the source of red-

shifts, magnitudes and types for the galaxies, as well as cluster definition and selection. The analysis of substructures on individual clusters is done in Sect. 3, while luminosity segregation is measured on the merged cluster sample (Sect. 4). The results are then discussed in Sect. 5.

2. The sample

The present work is based on a redshift catalogue involving the central regions of 15 clusters of different richnesses in the redshift range $0.01 \lesssim z \lesssim 0.06$ (Paper I). Note that several of the clusters are well studied, nearby objects like Centaurus and Abell 400 or have been extensively observed for specific purposes (e.g. Abell 3558: Bardelli et al. 1994). Inside these regions nearly complete (80%) redshift information down to $M_B \approx 18^{mag}$ could be obtained, as well as raw morphological types for most of the galaxies. The present sample differs from those of previous investigations because it concentrates onto the very cores of the clusters ($R < 0.5 \text{ h}^{-1} \text{ Mpc}$), and because of the homogeneity of kinematical information.

Cluster centers were chosen in order of preference from (a) published X-ray centers (Lahav et al. 1989, Edge & Stewart 1991), (b) the position of the cd-galaxy, if present, (c) the Abell cluster center or (d) by taking the center of the relevant Optopus field (see Paper I), which roughly coincides with the galaxy density peak. The only exception to this procedure was Abell 1736, whose OPTOPUS field was offset by $0.05 \text{ h}^{-1} \text{ Mpc}$ with respect to the X-ray center.

A common selection radius of $0.5 \text{ h}^{-1} \text{ Mpc}$ around each cluster centre was therefore chosen, using approximate mean cluster velocities and assuming all clusters to be located in the Hubble flow. For Hydra and Centaurus ($z \approx 0.01$) two adjacent fields had been taken, and for the other very nearby clusters data from the literature was available to help fill the region.

Table 1 lists the fields and also gives the name of each cluster around whose centre the selection has been done (2), kind of center determination (3), where X: X-rays, cd: cd-galaxy position, A: Abell center, O: center of Optopus field, as well as centre coordinates (4), and selection radius in arcminutes (5).

2.1. Membership selection

As a first step towards meaningful cluster definitions, we then looked at velocity histograms in the direction of all 15 fields, eliminating obvious (5σ) fore- or background galaxies. In one case (field 12) two distinct structures could be identified: the main cluster at $v = 4500 \text{ km s}^{-1}$ and a smaller group at $v = 11000 \text{ km s}^{-1}$. Moreover, some non-gaussian velocity histograms with indication of bimodality could be recognized. A statistical test was thus applied which returns the likelihood that the biggest gap in the dataset could occur in a normal distribution (adapted from the ROSTAT package, Beers et al. 1990). Only in the case of field 9 a gap was found whose size was inconsistent at the 5% level with an underlying gaussian distribution. Field 9 was thus considered bimodal and subdivided at $v = 11500 \text{ km s}^{-1}$, the big gap location. To assess final cluster

Table 1. Cluster sample

Field (1)	Name(s) (2)	C (3)	α (B1950) δ (4)	R (5)
1	Abell S0301, DC 0247-31	cd	02 47 27 -31 23 44	26'
2	Abell 0400	X	02 55 03 +05 49 32	26'
3	Abell 1016	cd	10 24 28 +11 15 56	19'
4	Abell 1060, Hydra	X	10 34 22 -27 15 58	45'
5	Abell S0639	O	10 37 48 -46 01	29'
6	Abell 3526, Centaurus	X	12 46 03 -41 02 28	48'
7	Abell S0721	A	13 03 18 -37 19 00	13'
8	Abell 3556	O	13 20 24 -31 27	13'
9	Abell 1736, DC 1324-27	X	13 24 46 -26 55 24	18'
10	CL 1322-30	O	13 22 00 -30 02	42'
11	Abell 3558, Shapley 8	X	13 25 08 -31 14 13	13'
12	Abell S805, DC 1842-63	cd	18 42 35 -63 23 04	40'
13	Abell 3733	cd	20 58 39 -28 15 22	16'
14	Abell 3880	cd	22 25 05 -30 49 52	11'
15	Abell 4038, Klemola 44	X	23 45 18 -28 26 00	21'

membership, a $3\text{-}\sigma$ clipping technique (Yahil & Vidal 1977) was then applied to each of the 17 galaxy units recognized so far. Table 2 lists the number of member galaxies after $3\text{-}\sigma$ clipping (column 3), as well as the resulting limits in redshift space (4).

Mean cluster velocities and velocity dispersions were then determined for each cluster in the sample, using biweight estimators (Beers et al. 1990). These estimators have the advantage of being robust against outliers and are particularly useful when working with small datasets. Cosmological effects are taken into consideration following Danese et al. (1980). The resulting values and their uncertainties are listed in Table 2, columns 5 and 6.

Our cluster mean velocities and velocity dispersions do agree quite well with those quoted by Struble & Rood (1991) and Girardi et al. (1993). Nevertheless, there are some cases where a discrepancy is found. The reason herefore must be related to the effect of substructures in the central cluster regions, which tend to inflate velocity dispersions, and to the presence of luminous galaxies of low dispersion in the cluster cores (as shown in the next sections). Nevertheless, given that our results are virtually free from larger scale contamination, we consider them good estimators of central mean velocity and velocity dispersion. With the present data it was not possible to discern the bimodal structure of Centaurus using a gapper test. For this reason we give a global value for the mean cluster velocity and for the velocity dispersion. Nevertheless, substructure is detected in this and in some of the other clusters, as we will see below. It may be, therefore, that the kinematic parameters given in Table 2 do not reflect the true dynamical state in 50% of the cases. They should be treated as first estimations and were calculated because a measure for the cluster dispersion is needed for the Lee-test simulations (see below).

Table 2. Redshift ranges and kinematical parameters

Field	Name(s)	#	cz -range [km s ⁻¹]	$\langle v \rangle \pm \Delta v$ [km s ⁻¹]	$\sigma \pm \Delta \sigma$ [km s ⁻¹]	inclusion flag
(1)	(2)	(3)	(4)	(5)	(6)	(7)
1	Abell S0301, DC 0247-31	25	5500–8000	6867±98	473±99	Y
2	Abell 0400	73	5500–8500	7057±65	547±57	Y
3	Abell 1016	22	9000–10500	9646±56	252±51	
4	Abell 1060, Hydra	76	2000–6000	3867±84	727±69	Y
5	Abell S0639	32	5500–7500	6194±78	431±52	Y
6	Abell 3526, Centaurus	64	1000–6000	3688±120	952±63	Y
7	Abell S0721	29	13500–16500	14936±134	703±70	Y
8	Abell 3556	30	13500–15500	14574±86	459±44	Y
9a		16	9500–11500	10537±102	385±60	
9b	Abell 1736, DC 1324-27	48	11500–16000	13734±130	889±81	Y
10	CL 1322-30	18	3500–5000	4222±70	278±52	
11	Abell 3558, Shapley 8	59	11000–18000	14242±155	1183±100	Y
12a	Abell S805, DC 1842-63	54	3000–6500	4603±87	621±64	Y
12b		11	10000–11500	10771±121	367±51	
13	Abell 3733	27	10000–13000	11716±103	522±84	Y
14	Abell 3880	22	15000–19000	17513±188	855±148	
15	Abell 4038, Klemola 44	59	7000–11000	8936±118	896±66	Y

Some of the galaxy samples are clearly too poor to be used for the substructure analysis and have to be discarded. Computation of the Dressler & Shectman (1988) substructure test requires the evaluation of velocity dispersions from samples of \sqrt{N} neighbours around each galaxy, where N is the total number of galaxies (Bird 1994). Given that 5 is a lower limit for the determination of standard deviations, we chose a number of $N \geq 5^2 = 25$ galaxies as the minimum richness.

We are thus left with 12 clusters (flag “Y” in Table 2, column 7) and a total of 576 galaxy redshifts, 2/3 of which are taken from Paper I and have mean errors well below 50 km s⁻¹.

2.2. Photometric data

As we wanted to look at dynamical friction effects, luminosity information was necessary. For three of the clusters detailed photometrical studies could already be found in the literature: A 3526 = Centaurus by Dickens et al. (1986), A S 805 by Millington & Peach (1989) and A 4038 by Green et al. (1990). In addition, b_j magnitudes from the COSMOS catalogue were kindly provided by H. MacGillivray (1993) for ten clusters of high galactic latitude. Given the selection of high latitude clusters no correction for reddening or extinction was applied.

A comparison of COSMOS magnitudes with those of Green et al. (1990) in A 4038 shows an excellent agreement, with differences of only a few hundredths magnitudes. For some of the brightest spiral galaxies COSMOS magnitudes were not available (due to the problem of resolved HII regions), which meant that magnitudes had to be taken from a bright galaxy catalogue. It should be noted that magnitudes from the COSMOS catalogue are b_j magnitudes, while those for Centaurus are G26.5 magnitudes, and for most of the other clusters generic optical magnitudes were taken from different sources. Magnitudes were not transformed to a common scale, because for our statistical

analysis a spread of a few tenths of magnitudes for individual galaxies could be taken into account.

2.3. Morphological data

Galaxy types were searched for in the literature, mainly resulting in a sample from Dressler’s (1980) and UGC (Nilson 1973) catalogues, as well as from Huchra’s (1991) collection, as implemented in the DIRA2 database (Astronet Data Base Group Italy, Bologna). All galaxies were then divided into three classes: E, S0 and S. In addition, many of the remaining galaxies were classified by the author into one of the above classes, after visual inspection of ESO–Schmidt plates. Because careful classification is difficult on this kind of plates, a check was made involving 105 galaxies with independently known types. Of these, 15 were classified by the author with an “earlier” type and 13 with a “later” type than literature values, corresponding to an agreement of around 75%.

3. Substructures

Ideally, substructure tests should be applied to galaxy samples which are complete in magnitude. Here, we will use all the available data without regard to the magnitudes, for different reasons. First, the small sample size makes any further restriction unreasonable. In addition, complete magnitude information is not available for all cluster fields. Nevertheless, in those fields where magnitudes were available from COSMOS, redshift completeness amounts to ca. 75% of the galaxies down to 18^{mag}. Given the small field of view and the extensive redshift coverage, we will concentrate on substructure analysis methods which make use of the velocity information. We chose the test of Dressler & Shectman (1988, hereafter DS–test), the Lee test (Fitchett 1988), and several tests that check for departures from normality of the galaxy velocity distribution. Note that:

a) For the DS-test we followed the same procedure as Bird (1994), using \sqrt{N} galaxies to define the neighbourhood of each galaxy, where N is the total number of galaxies involved in the analysis.

b) To assess the significance of substructure detections for the Lee test we performed the same test on 100 cluster simulations. Modelling of the simulated clusters was done with an $1/r$ galaxy density profile (Fitchett & Webster 1987) and with the same velocity dispersion as in Table 2. Steps of 4 degrees have been used for the orientation of the projection axis in the X-Y-cz plane. Note that the simulations for field 9b were done with an offset of $0.05 \text{ h}^{-1} \text{ Mpc}$ between the peak of the $1/r$ density distribution and the center of the circular selection region. A higher likelihood for the presence of substructure would result if the offset was not accounted for (92% instead of 87%).

c) Three different tests for normality have been employed, i.e. the U^2 , W^2 and A^2 tests taken from the ROSTAT package (Beers et al. 1990), the resulting significance being the mean from these three tests, which agree very well.

Each of these substructure tests has its strengths and weaknesses. For example, the DS-test measures the deviation of the local from the global kinematics, allowing to detect efficiently small offcenter groups, but sometimes failing in cases where two clumps of equal size and different mean velocities overlap in projection. On the other side, the Lee test is designed to be a very general maximum-likelihood method, but computational constraints confine its use to detecting bimodal structures of comparable size, thus being unable to state about the presence or absence of multimodal structures. It is also trivial that testing the gaussianity of a velocity sample alone cannot give clues about substructures which have same means and dispersions but differing locations in the plane of the sky. We see that all of these tests are bound to miss some manifestations of substructure, each one being sensitive to some particular configuration. For these reasons, a combination of all methods should allow a better judgement to be made. Our statement about the existence of substructure relies upon the fact that at least one of the three detection methods could find significant signs for it. Results are shown in Table 3, which gives field number (column 1), name of the cluster (2), significance level for the tests mentioned above (3–5), and total significance level for substructure (6), which is the highest value of columns 3, 4, and 5. As can be seen from the analysis results, 50% of the clusters show clear signs of substructure (5% significance level). This frequency of substructure in cluster cores has to be considered a lower level because of the intrinsic property of individual tests to miss some manifestations of substructure. It should be noted that the same order of magnitude for substructure frequency has been found by other authors (e.g. Escalera et al. 1994; West 1994), in particular also involving comparable spatial resolution but without redshift information (Salvador-Solé et al. 1993).

4. Segregation in velocity

Radial velocities and magnitudes had to be normalized before a kinematical analysis on the galaxy sample as a whole could

Table 3. Substructure analysis. Column 6 is the highest value of columns 3,4,5 and gives the final likelihood for the presence of substructure

Field (1)	Name (2)	DS-test (3)	Lee-test (4)	normality-tests (5)	total (6)
1	A S 301	71	38	57	71%
2	A 400	79	99	80	99%
4	A 1060	41	85	99	99%
5	A S 639	94	64	75	94%
6	A 3526	99	96	89	99%
7	A S 721	48	13	19	48%
8	A 3556	81	98	78	98%
9b	A 1736	99	87	34	99%
11	A 3558	51	28	36	51%
12a	A S 805	98	45	9	98%
13	A 3733	62	22	49	62%
15	A 4038	90	94	93	94%

be started. We chose the most straightforward methods, using absolute magnitudes M and velocities normalized by cluster mean velocity and velocity dispersion, i.e.:

$$\tilde{v}_i = \frac{v_i - \langle v \rangle}{\sigma} \quad (1)$$

This implies that \tilde{v}_i has a mean value of 0 and a standard deviation of 1 in each cluster. Normalized velocity dispersions

$$\sigma_w = \sqrt{\frac{\sum (\tilde{v}_i)^2}{N(N-1)}} \quad (2)$$

will be used in the following as kinematical indicators for different samples. Only galaxies brighter than $M = -19^{mag}$ have been included in the following analysis, which roughly corresponds to the completeness limit of the present dataset. Choosing only objects brighter than $M = -19$ also excludes dwarf galaxies, which could contaminate fainter samples (Binggeli et al. 1988).

4.1. Dependence on galaxy types

First, we looked at differences in the kinematical behaviour of galaxies depending on their morphology. It can be seen in Fig. 1 that there is a continuous trend of the velocity dispersion to increase from early to late galaxy types. Velocity dispersions have been computed with a biweight estimator of scale (Beers et al. 1990), which has shown to be superior when only few objects are involved. Error bars come from a bootstrapping calculation with 1000 iterations. Between E and S galaxy types a rise in the velocity dispersion of 30% can be observed. The hypothesis that E-galaxies have the same velocity dispersion as S0-galaxies cannot be excluded by an F-test (17% likelihood). The same is true for the difference between S0 and S-galaxies (23% likelihood of same underlying distribution), while the difference between E and S-galaxies is significant at a level of 3%.

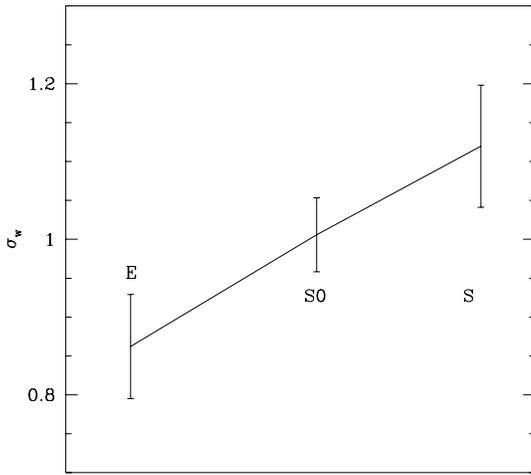


Fig. 1. Velocity dispersion for galaxies of different morphological classes.

4.2. Dependence on galaxy luminosity

In the present sample of galaxy clusters there are clear signs of velocity dispersion dependence on absolute magnitude for galaxies brighter than $M \approx -22^{mag}$, as can be seen in Fig. 2. Again, velocity dispersions have been computed with a biweight estimator of scale and error bars come from bootstrapping with 1000 repetitions. Bin limits were set every 0.5 mag between $M = -23.5^{mag}$ and $M = -19.0^{mag}$, taking the biweight mean value $\langle M \rangle$ in each bin as the x-position instead of the bin center. Further dividing the sample into galaxies of different types reveals that mainly the most luminous early type galaxies are responsible for the lower velocity dispersion. However, there is a general tendency of ellipticals to have lower dispersions than spirals also at the faint end. Former effect cannot be due exclusively to the existence of D/cD galaxies residing in the bottom of the potential well, because only 4 of the clusters are given a Bautz–Morgan type I (Abell et al. 1989). Another hint is that there are no E–galaxies with normalized velocities larger than 1.2 down to -20.6^{mag} , while 6 or 7 would be expected from a normal distribution with $\sigma_w = 1$. No clear indication about the kinematical status of S0 galaxies was found. It is widely known that there is considerable danger of confusion while classifying S0 galaxies as an intermediate class between E and S (Bender 1992). This uncertainty in the morphological classification, together with the low number of S0 galaxies brighter than $M = -22^{mag}$ in our sample, makes it difficult to state about the presence of luminosity segregation in this class. It seems that the brightest S0 galaxies lie very close to the kinematical center of the cluster, indicating that these galaxies have been residing in the centers of clusters for long periods of time. On the other side, no signs of velocity dispersion changes with luminosity can be seen for E or S0 galaxies fainter than $M = -21.5^{mag}$. This can be explained by the fact that the time-scale for dynamical friction exceeds the Hubble time when galaxies of luminosity lower than L_* are involved (Sarazin 1988).

As can be seen in Fig. 2, there is a deviating galaxy with

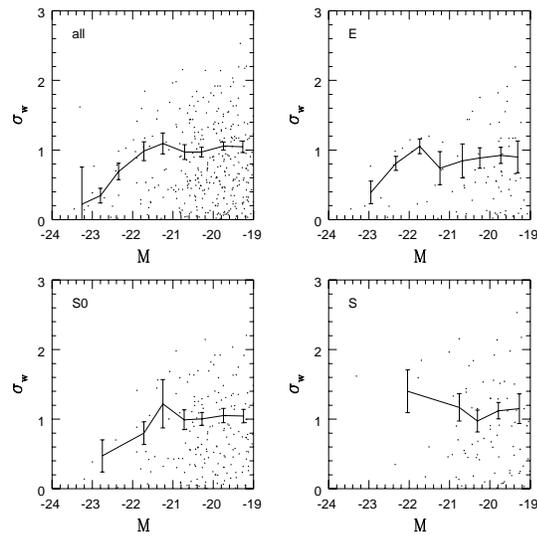


Fig. 2. Velocity dispersions for galaxies of different absolute magnitudes.

$M \approx -23.2^{mag}$ and $\sigma_w \approx 1.6$, which was classified as S by Nilson (1973). Inspection of the corresponding photographic plate reveals that the object is of peculiar nature, possibly interacting with its neighbours. Its morphological type is given as uncertain in several other catalogues, ranging between S0 and Scd.

5. Discussion

We analysed the kinematics of the core regions of 12 nearby galaxy clusters. The homogeneous redshift sample was nearly complete down to faint limits ($\lesssim 18\text{--}19^{mag}$) and was supplemented by magnitudes and rough morphological types for most of the galaxies. An analysis of substructure using velocity data revealed that 50% of the cluster cores harbour significant substructure, thus confirming that many clusters are not even relaxed in their inner regions, where effects like mass segregation and infalling groups of galaxies might be disturbing the virialization process.

After having merged the data to a sample of normalized galaxy velocities, magnitudes and types, we looked for type and type/luminosity segregation in velocity space. Previous findings (Binggeli et al. 1987; Sodr  et al. 1989) about early type galaxies having lower velocity dispersions than late types are confirmed by the present analysis. Zabludoff & Franx (1993) found no such relation, on the opposite they claimed deviations in the velocity means between different types, concluding that there must be groups of spirals falling onto the cluster main body and distorting the distribution of velocities. Their findings should be considered complementary to ours, because of the different scale observed ($R \leq 0.5 \text{ h}^{-1} \text{ Mpc}$ versus $R \lesssim 1.5 \text{ h}^{-1} \text{ Mpc}$).

Luminosity segregation in velocity space is also present, qualitatively and quantitatively in agreement with the findings of Biviano et al. (1992), who were using a larger, but more het-

erogeneous data sample. Moreover, there is a link between type and luminosity segregation. Only the brightest E and, possibly, S0-galaxies ($M \lesssim -22^{mag}$) show clear signs of the phenomenon of luminosity segregation in velocity, which is probably related to two-body relaxation effects. These galaxies are responsible for the differences in velocity dispersion between early and late galaxy types, plausibly representing the fraction of galaxy population in clusters which have undergone significant late dynamical evolution. On the other side, S-galaxies show no sign of luminosity segregation, as is expected from objects that are still infalling onto the cluster main body and are presumably crossing the core region for the first time.

It remains uncertain whether the effect is due to dynamical friction or comes from the fact that galaxies which are the result of repeated mergers will tend to have velocities closer to the cluster mean. In both cases, strong evolution in the dynamics of the oldest cluster population can be seen. Capelato et al. (1981) found several hints for the presence of partial equipartition of galaxy kinetic energies in clusters. If the M/L ratio is close to constant for E-galaxies, then our findings support their view that only the most massive galaxies had had enough time to slow down.

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