Chapter 1

OPTICAL ANALYSIS OF CLUSTER MERGERS

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Abstract An increasing amount of data has revealed that many clusters are very complex systems. Optical analyses show that several clusters contain subsystems of galaxies, suggesting that they are still in the phase of dynamical relaxation. Indeed, there is a growing evidence that these subsystems arise as the consequence of group/cluster mergers. We here review the state of art of optical search and characterization of cluster substructures. We describe the effects cluster mergers have on optical measures of cluster dynamics, and on the properties of cluster member galaxies. We also discuss cluster mergers in relation to the large scale structure of the universe.

Keywords: Clusters: general, galaxies: evolution, cosmology, interactions

1. INTRODUCTION

Until the 80's clusters have been modeled as virialized spherically symmetric systems (e.g., Kent & Gunn 1982). Rather, clusters often contain subsystems of galaxies, usually called substructures or subclusters. Indeed, in the hierarchical scenario of large scale formation it is quite natural to expect that clusters form from the merger of small subclumps (e.g., Colberg et al. 1999). In this context, the presence of substructures is indicative of a cluster in an early phase of the process of dynamical relaxation, or of secondary infall of clumps of galaxies into already virialized clusters.

The presence of substructures complicates the theoretical modeling of cluster dynamics. On the other hand the existence of substructures is probably an essential ingredient in the formation and evolution processes of clusters and their components, so that the analysis of substructures could provide useful cosmological constraints.

Historically, the discovery of substructure occurred in the optical band, via the analysis of the projected distribution of cluster galaxies (e.g., Wolf 1902; Shane & Wirtanen 1954). In the X–ray, Jones et al.'s (1979) Einstein IPC images first showed the complex structure of the hot intra–cluster gas of many clusters. In the radio, Hanisch (1982) and Vestrand (1982) were the first to suggest that the presence of a radio–halo in clusters was related to a short–lived dynamical configuration (see also Feretti 2000). Only recently, new insights into the subclustering phenomenon have come from optical observations of gravitational lensing in galaxy clusters (e.g., Kneib et al. 1996; Pierre et al. 1996; AbdelSalam et al. 1998; Clowe et al. 2000; Hoekstra et al. 2000; Metzger & Ma 2000).

In this review, we consider substructures from the point of view of the analysis of cluster members. Strictly speaking, "optical analysis" of substructures should cover also the weak lensing analyses mentioned before, but the application of this technique to the detection of subclusters is quite recent, and we have decided not to consider it here. Weak lensing analyses are likely to become more and more important in the near future, as they directly detect subclustering in the mass component, rather than relying on galaxies as tracers of the potential. The most exciting possibility is the existence of "dark clumps" of matter traced by no galaxies (Erben et al. 2000; Umetsu & Futamase 2000). We refer the interested reader to Fort & Mellier (1994) for a general review on gravitational lensing from clusters, and to Fitchett (1988a) and West (1994a) for previous reviews on the topic of subclustering.

This review is organized as follows. In § 2 we review the techniques used for the detection of substructure and their results; in § 3 we describe the physical nature of substructures and their connection with ongoing cluster mergers; in § 4 we describe the effects of mergers on estimates of the dynamical properties of clusters; in § 5 we discuss substructure in relation to cosmology and the large scale structure of the Universe (LSS hereafter); finally, in § 6 we review our current knowledge of the relation between cluster mergers and the properties and evolution of cluster galaxies.

For the sake of homogeneity with other contributions in this book, a Hubble constant of 50 km s^{-1} Mpc^{-1} and a deceleration parameter $q_0 = 0.5$ are used throughout.

2. DETECTING AND QUANTIFYING SUBSTRUCTURE

While the first indications of the existence of subclusters were already present in the maps of Wolf (1902), and Shane & Wirtanen (1954), the first modern analyses of the subclustering phenomenon date to the early 60's. Van den Bergh (1960, 1961) compared the observed distributions of velocity differences among galaxy pairs in Virgo and Coma to those obtained from azimuthal scramblings of the data–sets, and found evidence of subclustering in both clusters, on scales ~ 0.15 Mpc. In the same period, de Vaucouleurs (1961) suggested that Virgo was not a single cluster but the overlap of two subclumps with different galaxy populations and kinematics. Substructure in the two–dimensional (2D) distribution of galaxies was examined for other clusters by Abell et al. (1964). In the 70's, White's (1976) numerical simulations indicated that clusters form by the coalescence of subclusters, and this prompted several authors (most notably Baier & Ziener 1977; Baier 1984; Geller & Beers 1982) to undertake a systematic analysis of substructure in the galaxy distributions of several clusters. Following these preliminary studies, many new techniques have been developed to analyze the problem of substructures. Despite an increased sophistication in the analysis, subclustering remains difficult to measure in a meaningful, quantitative, and unambiguous way. Due to the lack of full kinematical and dynamical information, all statistical methods need to rely on simulations to quantify the significance levels of the detected substructures.

Some of the techniques that have been developed for the detection of substructure in the distribution of galaxies in clusters only provide the probability that a given cluster contains significant substructures; others are able to characterize the properties of the detected substructures, and even to assign the probability of individual galaxies to belong to a given subcluster. Most methods only use the positions and velocities of cluster galaxies, but some do make use of internal galaxy properties – such as their morphologies, luminosities, colours, and star formation rates – to better characterize the substructures (see, e.g., Gurzadyan et al. 1994; Serna & Gerbal 1996). These more sophisticated methods have so far been applied only to a few clusters. A further step in improving the characterization of subclusters consists in using the relative distances of galaxies in a cluster, in lieu of their relative velocities. So far, this has

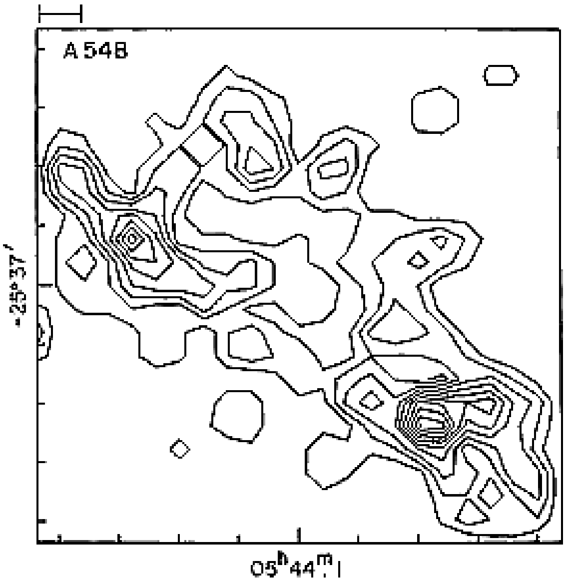

Figure 1.1. Galaxy surface number density diagram of ABCG 548. The bar to the upper left represents 0.48 Mpc at the cluster distance. Taken from Geller & Beers (1982).

been possible only for very nearby clusters, such as Virgo (Federspiel et al. 1998; Neilsen & Tsvetanov 2000) and Centaurus (Lucey et al. 1986).

Powerful constraints on cluster substructures come from the comparison of the distribution of cluster galaxies with the surface brightness and temperature maps in the X–ray (e.g., Bird et al. 1995; Arnaud et al. 2000; Gomez et al. 2000; Kolokotronis et al. 2001; Shibata et al. 2001). We discuss the results of these comparisons in more detail in § 4.

The most commonly used statistical methods for the detection of substructure can be grouped in three classes: (a) methods in which only the galaxy positions are used, (b) methods in which only the galaxy redshifts are used, or (c) methods in which the combined spatial and kinematical galaxy properties are used. Several methods can be equally applied to the distribution of galaxy positions, of galaxy velocities, or both, so that the above distinction is rather artificial, and we adopt it here for our convenience.

2.1. SPATIAL SUBSTRUCTURE

The main advantage of searching for substructures in the projected distribution of galaxies, is the availability of large data–sets, reaching thousands of galaxy positions for nearby clusters. On the other hand, these methods suffer from contamination by fore/background galaxies, groups, and other clusters.

Geller & Beers (1982) were the first to systematically address the evidence of substructures in the projected distributions of cluster galaxies. Using smoothed density–contour maps in 65 clusters, they identified substructures as regions where the local density contrast was more than 3–σ above the background fluctuations (see Fig. 1.1).

West et al. (1988) developed three new statistical tests: the *β statistics* measures departures from mirror symmetry in clusters; the *angular separation test* detects subclustering by looking for significant galaxy overdensities at similar polar angles relative to the cluster centre; the *density contrast test* is similar to the method of Geller & Beers (1982).

The application of the *Lee–method* (Lee 1979) to clusters of galaxies is described in Fitchett & Webster (1987; see also Fitchett 1988b). The method optimally splits a data–set into two or more groups using a maximum–likelihood statistics. In practice, the method is only used for the partition of a sample into two subsamples, as the detection of more than two clumps is computer–time consuming. The method measures the clumpiness, L, of the 2D data projected onto a line, with a given orientation, α. The analysis of the function $L(\alpha)$ allows one to define the two groups. The significance of L is established by comparison to Monte Carlo simulations, in which the simulated galaxy distributions can be drawn from several kinds of surface density profiles. While initially applied to 2D data–sets, the *Lee–method* method has later been used also in its 1D and 3D versions (Fitchett & Merritt 1988).

The *Wavelet transform* method is described by Slezak et al. (1990). The basic idea is to convolve the 2D Dirac distribution of galaxy positions with a chosen zero–mean function of position and scale (the Wavelet), on a grid of pixels. There are different kinds of Wavelet function; the so–called 2D radial "Mexican Hat" (the second derivative of a Gaussian) is often used for studies of galaxy clusters (e.g., Escalera & Mazure 1992; Escalera et al. 1992). By varying the scale of the Wavelet function, one is able to test for the presence of substructure of different sizes (a multi–scale analysis). A given substructure can only be detected if its characteristic size is of the order of the scale of the Wavelet. It is worth pointing out that, despite of being circularly symmetric, the radial Wavelet can detect non–circular substructures. As usual, Monte Carlo simulations are needed to establish the statistical significance of the detected substructures. The method also provides the likelihood of individual galaxies to belong to given substructures, thus in practice allowing a decomposition of the cluster into its component subclusters.

A variant of the classical *Wavelet* method has been recently discussed by Shao & Zhao (1999). An extension of the *Wavelet* method to 3D is discussed below (see § 2.3).

Starting from statistical techniques generally used in the analysis of the LSS of the universe, Salvador–Solé et al. (1993a,b) implemented and applied the *average two point correlation function* to the study of cluster substructures. This method provides an estimate of the scale length of typical substructures.

The *KMM* mixture–modeling algorithm for the decomposition of a given data–set in two or more groups, described by Ashman et al. (1994), has been applied to the spatial distribution of cluster galaxies by, e.g., Kriessler & Beers (1997), Maurogordato et al. (2000). Since the simpler implementation of *KMM* is for a 1D distribution, we describe it at length in the next section.

2.2. VELOCITY SUBSTRUCTURE

Models for cluster evolution predict that a system of gravitationally bound particles relaxes into a Maxwellian velocity distribution. A Gaussian distribution of line–of–sight (l.o.s.) velocities is therefore expected (e.g., Ueda et al. 1993). A non–Gaussian distribution of the observed cluster member velocities is therefore indicative of a non–relaxed dynamical state. For this reasons, *shape estimators* have been used for the detection of substructure in the velocity distribution of cluster members. The classical shape estimators are the kurtosis and the skewness; more robust estimators are the asymmetry– and tail–index (Bird & Beers 1993). The main problem of this method is that the shape of the velocity distribution is not only affected by the presence of substructures, but also by velocity anisotropies (which change the kurtosis, see Merritt 1987), and by the inevitable contamination of the cluster velocity distribution by foreground and background galaxies. In this sense, an improved technique has been developed by Zabludoff et al. (1993). Their technique only works properly for well–sampled data–sets (at least 100 galaxies with velocities). It works by a decomposition of the cluster velocity distribution into a sum of orthogonal Gauss–Hermite functions, and it provides an estimation of the 3rd and 4th order moments, robust against the effect of interlopers.

An alternative way to look for deviation from a relaxed velocity configuration, is to compare the mean cluster velocity with the velocity of the cD galaxy (if present). In fact it has been argued by Beers et al. (1991) that cD galaxies with velocity offsets are only found in clusters with substructures (but see Lazzati & Chincarini 1998 for a different point of view). There are clusters where significant substructure has been found and yet display a Gaussian velocity distribution, but, at the same time, with a significant cD velocity offset (e.g., Pinkney et al. 1993). We will develop this topic further in § 6.1.

More sophisticated methods have been developed for the detection of multi–modality in the velocity distribution of cluster galaxies. Ashman et al. (1994) described the use of the *KMM algorithm,* a mixture–modeling algorithm, for the detection of substructures in galaxy clusters. *KMM* uses maximum likelihood statistics to determine the optimal partition of a given data–set into an *a priori* chosen number N of Gaussian distributions. The method provides the relative probabilities of group memberships for all galaxies in the data–set. Using the maximum–likelihood ratio test, it estimates the probability that the given partition into N groups is a significantly better description of the distribution than the single group hypothesis. The correct number of groups N corresponds to the solution with the highest probability. *KMM* has also been applied to the distribution of galaxy positions (e.g., Kriessler & Beers 1997) and to the distribution of galaxy positions and velocities (e.g., Bird 1994a; Colless & Dunn 1996, see Fig. 1.2). The *Dedica* method, based on adaptive–kernels, developed by Pisani (1993), has the advantage of giving a non–parametric estimate of the clustering pattern of a data sample, without any *a priori* hypothesis neither on the number of groups, nor on the group distribution function. *Dedica* provides the significance of each subcluster in the velocity distribution, and the membership probability of each galaxy. Non–member galaxies are naturally rejected in this method (see Fadda et al. 1996 and Girardi et al. 1996 for an application of this method to a large cluster sample, see Fig. 1.3). *Dedica* has been extended to the analysis of subclustering in the combined spatial and velocity distributions by Pisani (1996; see Bardelli et al. 1998a for a recent application). Other non–parametric density estimators are the *Maximum Penalized Likelihood* technique (Merritt & Tremblay 1994) and the *Wavelet* method (see, e.g., Fadda et al. 1998 and § 2.1).

2.3. SPATIAL–VELOCITY SUBSTRUCTURE

The existence of correlations between the positions and velocities of cluster galaxies is a footprint of real substructures. Those methods that make use of both positions and velocities of cluster galaxies to search for substructures, are certainly the most reliable, but they are also the most demanding in terms of observational data.

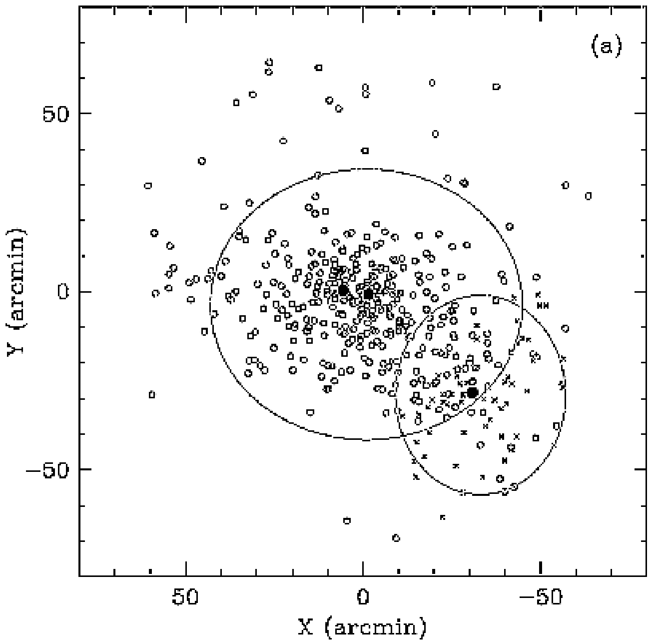

Figure 1.2. The partition of Coma into two subclusters by the *KMM algorithm.* Galaxies belonging to the main cluster are shown as circles and those in the NGC 4839 subcluster are shown as crosses. The dotted ellipses are the 2σ contours of the fitted Gaussians. Taken from Colless & Dunn (1996).

The most widely used of these methods is the Δ *statistics* devised by Dressler & Shectman (1988). The method considers all possible subgroups of 10 neighbours around each cluster galaxy, and computes the cumulative difference of these group mean velocities and velocity dispersions from the global cluster values. Galaxies located in groups with significantly different kinematical properties give a higher signal in the Δ *statistics*, see Fig. 1.4. Montecarlo simulations are run to establish the significance of the Δ *statistics,* by randomly shuffling the velocities and positions of the cluster galaxies. Another method that makes use of both galaxy positions and velocities is the *non–hierarchical taxonomical method* of Perea et al. (1986a,b), where the relative variance of positions and velocities is used for scaling these coordinates. To our knowledge, this method has only been applied to the Coma/ABCG 1367 supercluster complex and to the Cancer cluster.

Other methods are 3D versions of previously described methods (see § 2.1 and 2.2). In the 3D implementation of the *Lee–method* (see, e.g.,

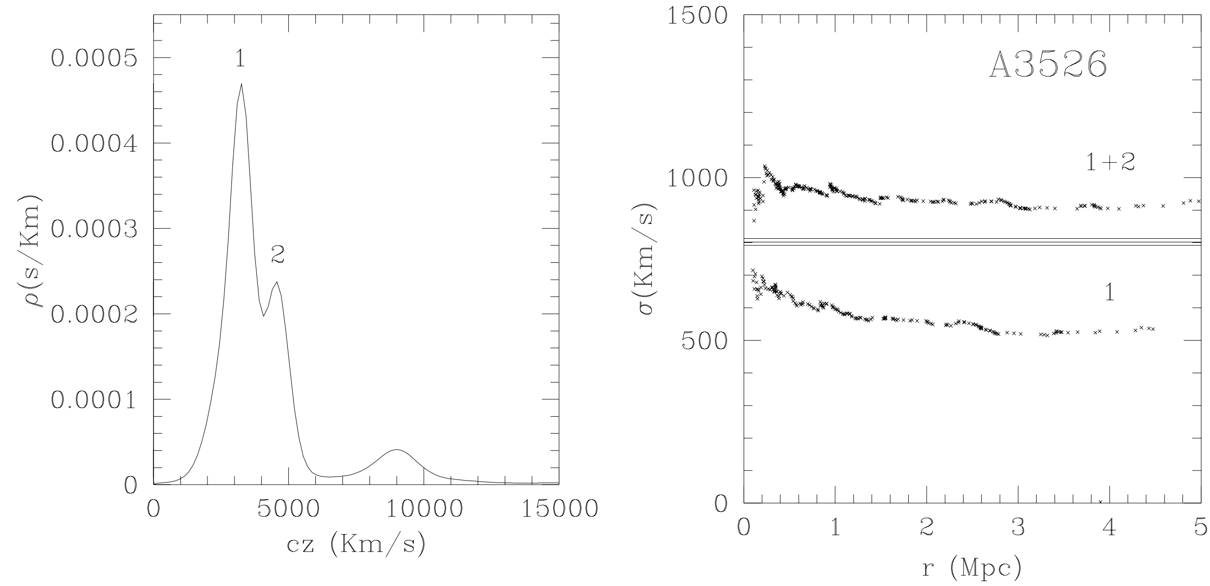

Figure 1.3. The double peaked velocity–space galaxy density of ABCG 3526 (Centaurus), as provided by *Dedica* (Pisani 1993), where the y–axis is in arbitrary units (left panel). The integral velocity dispersion profiles corresponding to the most important peak and the two peaks together; the horizontal lines give the value of the velocity dispersion and 1σ confidence levels, obtained from the X–ray temperature under the condition of perfect galaxy/gas energy equipartition, i.e. $\beta_{spec} = 1$ (right panel). Taken from Girardi et al. (1996).

Fitchett & Webster 1987), the data are projected onto a line, allowed to rotate in a volume, rather than in a plane as in its 2D version. The *3D Lee–method* has two interesting properties: it combines the spatial information with the l.o.s. velocity information without any arbitrary scaling; it is independent of linear coordinate transformation, so that it does not artificially detect substructure in an elliptical cluster. The *3D Wavelet* analysis uses spatial and kinematic information by weighting each galaxy (represented by a Dirac function) with a "local kinematic estimator" borrowed from the Dressler & Shectman test (Escalera & Mazure 1992; Escalera et al. 1992). Escalera et al (1994) and Girardi et al. (1997a) applied this method to large cluster samples (see Fig. 1.5). Needless to say, for both tests, the significance level of detected substructures is again established through the comparison with Montecarlo simulations. Another test originally developed for the analysis of 1D data–sets, *Dedica* has been extended to 3D by Pisani (1996). In this method the locally optimal metric is estimated, thus improving the per-

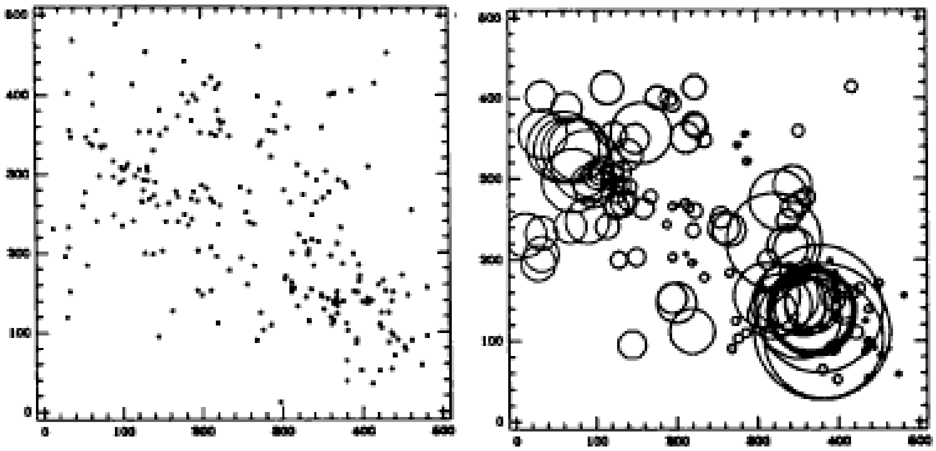

Figure 1.4. Map of the cluster ABCG 548 analyzed using Δ–*statistics.* Distribution of all galaxies in the cluster (left panel), and galaxies with known velocities marked by a circle whose diameter scales with the deviation of the local kinematics (right panel) Taken from Dressler & Shectman (1988).

formance of the density estimator. Within *Dedica* it is also possible to examine to what extent the large and small scale structures affect the estimation of the cluster dynamical parameters (e.g., the virial mass).

Other methods try to establish the presence of substructures by the direct dynamical influence they have on the cluster. These are the *S–tree technique* of Gurzadyan et al. (1994) and the *h–method* of Serna & Gerbal (1996). These methods assume a proportionality between a galaxy luminosity and its mass, and therefore need galaxy magnitudes. The *S–tree technique* is based on the properties of the flow of geodesics in phase space, and uses the so–called 2D curvature for evaluating how strongly bound is a subsystem. The *h–method* by Serna & Gerbal (1996) uses the relative binding energy in the hierarchical clustering method.

2.4. DIFFERENT METHODS COMPARED

Pinkney et al. (1996) tested the efficiency of several methods for the detection of substructure via the analysis of N–body numerical simulations of cluster mergers. Only the simplest methods were considered, those which do not try to detect and characterize the individual subclusters, but which simply provide a probability for a given cluster to contain significant substructures. In particular, the *Wavelet* method, *KMM*, and *Dedica* were *not* considered by Pinkney et al. (1996). In general, these authors found that the higher the dimensionality of the test, the more

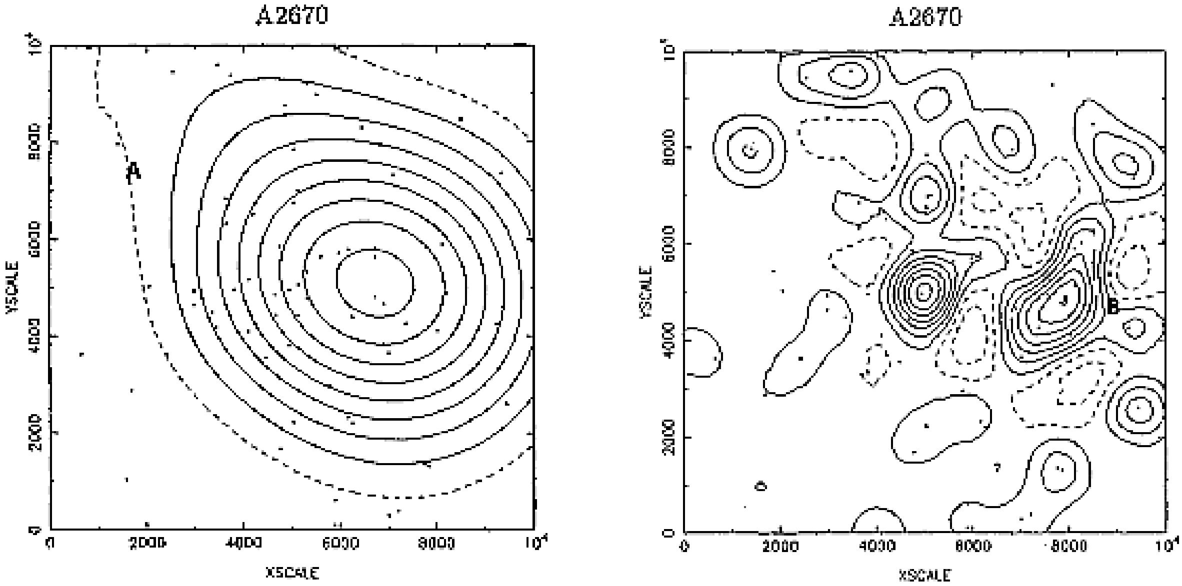

Figure 1.5. Results of the *Wavelet* analysis applied to a 3D sample of ABCG 2670. Left panel: the Wavelet image on the large scale; right panel: the Wavelet image on small scales. The cluster appears unimodal at large scales, but shows a structure in the core when examined at small scales. Taken from Escalera et al. (1994).

sensitive it is to substructure. However, the test sensitivity depends on the angle between the l.o.s. and the merger axis (e.g., those tests that consider galaxy positions only are most sensitive to l.o.s. perpendicular to the merger axis). As a consequence, a battery of different tests is recommended when searching for cluster substructures.

According to Pinkney et al. (1996), the most sensitive of the tests they considered turned out to be Dressler & Shectman's (1988) Δ *statistics.* In agreement with Pinkney et al.'s result, Flores et al. (2000) found evidence for substructure in the cluster ABCG 3266 with the Δ *statistics,* whereas the velocity distribution was found to be Gaussian. The N–body simulations of Crone et al. (1996) and Knebe & Müller (2000) confirmed the good overall performance of Dressler & Shectman's (1988) test, particularly for the case of recent big mergers, whereas small infalling groups remain difficult to detect.

For what concerns the comparison of more sophisticated tests, Fadda et al. (1998) found that the *Wavelet* technique and *Dedica* perform similarly, although Bardelli et al. (1998a) found the latter to be faster and more efficient. The *Wavelet* technique was found to give similar results to those of the *Lee–method,* when applied to detection of substructures in the Coma cluster (Escalera et al. 1992). The good performance of the *Lee* test was also confirmed in Crone et al.'s analysis of their numerical simulated clusters. The 2D *KMM* test was used by Maurogordato et al. (2000) to establish the presence of substructures in the cluster A521, whose galaxy velocity distribution is nevertheless Gaussian.

3. FREQUENCY AND NATURE OF SUBCLUSTERS

The analysis of subclustering aims at answering the following main questions: (i) what is the fraction of clusters harbouring substructure, and (ii) which are the subcluster properties. Here we try to summarize the results obtained in the most extensive and accurate investigations of cluster substructures, but we note that the answers to the above questions depend somewhat upon the amount of photometric and spectroscopic data available for the galaxies of the clusters considered (cf. the Coma cluster, Biviano 1998).

There is a general agreement that substructures concern $30-60$ % of all clusters (with a few notable exceptions: West & Bothun 1990; Rhee et al. 1991). This general consensus is built upon the independent results obtained from the analysis of substructures in the projected distribution of cluster galaxies (see, e.g., Geller & Beers 1982, who considered a sample of 65 clusters; Salvador–Solé et al. 1993a, 14 clusters; Kriessler & Beers 1997, 56 clusters), in the velocity distribution (e.g., Bird & Beers 1993, who analysed 14 clusters), and in the combined spatial and kinematical distribution (e.g., Dressler & Shectman 1988, who considered 15 clusters; Biviano et al. 1997, 25 clusters; Girardi et al. 1997a, 48 clusters; Stein 1997, 12 clusters; Solanes et al. 1999, 67 clusters). A higher frequency, $\sim 80\%$, is sometimes found when considering a battery of several tests (see, e.g., Bird 1994b who considered 25 cluster; Escalera et al. 1994 who considered 16 clusters).

The detected substructures generally have sizes of 0.4–0.6 Mpc (e.g., Geller & Beers 1982; Salvador–Solé et al. 1993b; Escalera et al. 1994; Girardi et al. 1997a), and their masses and richnesses are typically $\sim 10\%$ those of their parent cluster (Escalera et al. 1994; Girardi et al. 1997a). Larger size substructures (e.g. bimodal clusters) are less common and concern $10-20$ % of clusters (e.g., Girardi et al. 1997a, 1998). Subclusters of smaller sizes, ~ 0.2 Mpc, composed by a bright galaxy surrounded by dwarf companions, have been described by Ferguson (1992), Conselice & Gallagher (1998) and Kambas et al. (2000). After all, it might well be that a whole hierarchy of subclustering exists; Tully (1987) and Zabludoff & Mulchaey (1998) presented evidence for substructures in poor groups, and, on the largest scales, the superclusters are found to be substructured in clusters and groups (see § 5.1).

What is the physical nature of these subclusters? As pointed out by West & Bothun (1990), one can assign substructures to one of the following classes: (1) subclusters which are the surviving remnants of galaxy systems which have merged (or are in the merging phase) to form a rich cluster; (2) subclusters which presently reside within an otherwise relaxed cluster, perhaps arising from secondary infall of bound groups, in the phase of tidal disruption within the cluster; (3) galaxy groups which are bound to the cluster but are still outside the cluster virial region; (4) groups of galaxies dynamically disjoint from the cluster, which appear as substructures because of chance projection along the line of sight. Only substructures of the first class are truly representative of a young cluster dynamical status. For the sake of completeness, one should also mention the possibility that a specific type of substructure, the galaxy *aggregates* of Conselice & Gallagher (1998), i.e. clouds of dwarfs around a bright central galaxy, are just a manifestation of gravitational lensing of background galaxies by the mass of the bright central galaxy.

In principle, independent distance information is needed to assess the nature of the detected substructure (see Lucey et al. 1986; Federspiel et al. 1998; Neilsen & Tsvetanov 2000), but the inclusion of velocity data in the substructure analysis already reduces the probability of a chance projection.

The case of bimodal clusters, in particular, can be reduced to a simple two–body problem with linear motion (i.e., no rotational support) with a boundary value of separation $R = 0$ at time $T = 0$ (see, e.g., Gregory & Thompson 1984; Beers et al. 1992). Based on observational quantities (i.e. l.o.s. velocity, projected separation, and total mass of the system) one can then estimate the probability that: (a) the system is bound but still expanding, (b) the system is collapsing, or (c) the two clumps are not bound (see Lubin et al. 1998 for a recent application of this method to a bimodal cluster at $z \sim 0.8$). In more complicated cases of subclustering, it is possible to try to reproduce the observed galaxy distributions in positions and velocities, with numerical simulations, see e.g., Roettiger et al. (1997); Lubin et al. (1998); Flores et al. (2000); Roettiger & Flores (2000).

Cosmological N–body simulations have been used to test the sensitivity to projection effects of classical tests for substructure detection. Some have found the tests to be quite robust (e.g., Crone et al. 1996), but others (e.g., Cen 1997; Knebe & Müller 2000) have instead found that projection effects significantly inflate the estimation of the frequency of cluster substructure. These discrepant results can partly be ascribed to the difficulty of analysing simulated clusters in the same way as real clusters, in particular for what cluster member identification is concerned. Kolokotronis et al. (2001), in a recent analysis of 22 rich clusters, found evidence of substructures in 10 of them, both in X–ray and in the optical, while in another 5 clusters, the optical evidence for substructure is not supported by the X–ray analysis. Taken at face value, their result implies that 1/3 of the optically detected substructures are due to projection effects, but we note that their observed frequency of optically detected substructures is above the average found in other studies.

Assuming that most optically–detected substructures are real, what are they? Substructure of large sizes, i.e. bimodal clusters, are clearly equal–mass clusters caught in the process of merging. Smaller size substructures, on the other hand, could be identified either with small groups accreted by the cluster, or with the dense cores of clusters which have survived tidal disruption during the merger with a similar mass cluster (González–Casado et al. 1994). Schindler et al. (1999) have found in the Virgo cluster that the poorer the subcluster the more compact it is, both in the optical and the X–rays, as expected if subclusters origin from virialized groups. This issue is critical, since the accretion rate required for explaining the frequency of observed substructures depends on their survival time within the cluster, which is larger for dense cluster cores than for loose poor groups (see also § 5.2). In general, numerical simulations (see, e.g., Burns et al. 1994) have indicated that after a collision the group galaxies are dispersed over a very wide area. Many subcluster particles disperse on both side of the cluster along the merger axis. It is therefore generally assumed that compact subclusters, with a velocity dispersion characteristic of groups, are pre–merger. It is also instructive to compare the subcluster galaxy distribution with the gas surface brightness, since the collisional gas component is expected to be displaced downstream during the infall (see, e.g., Donnelly et al. 1999; Neumann et al. 2001).

4. DYNAMICAL EFFECTS OF CLUSTER MERGERS

Much of our knowledge on the dynamical effects of cluster mergers is based on the results of N–body simulations (see, e.g., Schindler & Böhringer 1993; Pinkney et al. 1996; Roettiger et al. 1996, 1997). These have shown that during a cluster merger the velocity dispersion of galaxies of whole structure can be strongly enhanced, up to a factor two, depending on the relative position of the merging axis to the l.o.s., the relative masses of the two clumps, and the epoch of merging (see

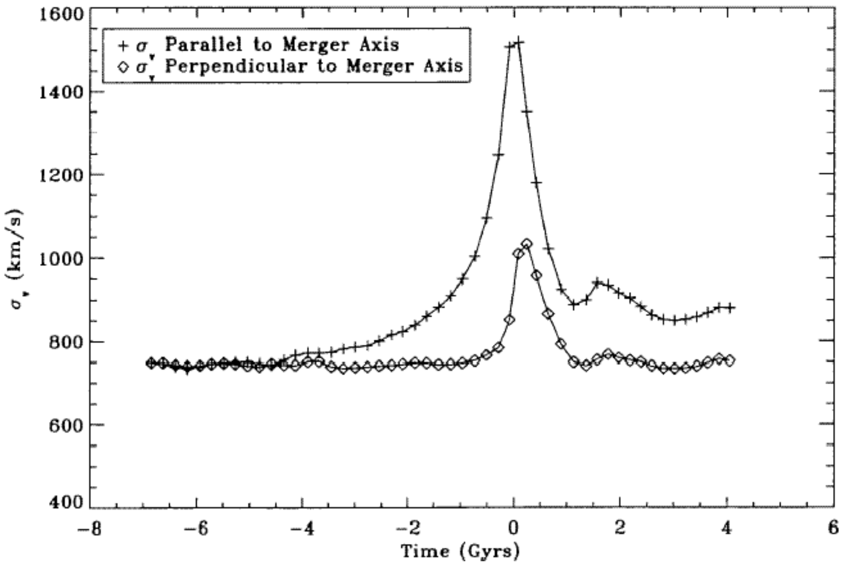

Figure 1.6. Velocity dispersion vs. time for a 3:1 mass ratio merger simulation and for two different viewing angles. Taken from Pinkney et al. (1996).

Fig. 1.6). Part of the (huge) large–scale motion energy of the subcluster (10^{50-60} erg, see, e.g., Bardelli et al. 2001) is converted into random motion of the galaxies of both the infalling group and the main cluster (Pinkney et al. 1996). Significant mass overestimation might result from a dull application of the virial theorem, if the system is observed within ± 1 Gyr from the epoch of core passage, the l.o.s. is close to the merger axis, and the mass ratio of the merging units is close to unity. For these extreme cases of mergers, in agreement with the results of numerical simulations, observational studies have indicated that the virial theorem would overestimate the mass of a cluster, typically by a factor 2, *if subclustering is ignored in the analysis* (Beers et al. 1991, 1992; Escalera et al. 1994; Girardi et al. 1997a; Flores et al. 2000; Maurogordato et al. 2000). Since the luminosity functions of galaxies in and outside subclusters are similar (Bardelli et al. 1998b), the mass–to–light ratio is similarly affected as the virial mass.

However, in such merging conditions, the distribution of galaxy velocities is strongly affected, and becomes skewed or double–peaked, so that a careful analysis of the velocity distribution can reveal the ongoing merger, and correct the mass estimate accordingly (see, e.g. Girardi et al. 1998). As an example, Fadda et al. (1996), using the adaptive kernel method (Pisani 1993), treated separately those peaks in the velocity distribution of cluster members, which are more distant than 1000 km s^{-1} and overlap for less than 20% of their galaxy population. However, as noted by Pinkney et al. (1996), during the core passage the two clumps could be so far in velocity ($\sim$ 3000 km s^{-1}) that the real issue is to understand whether the clumps are physically associated or seen in projection, rather than to provide a correct estimate of the velocity dispersion of the systems.

For what concerns the more common small substructures, Escalera et al. (1994) and Girardi et al. (1997a) showed that the effect of substructure on the virial mass estimation is marginal, $\sim$ 10%. Bird (1995) however found a much larger effect of substructures on the estimations of cluster masses. The discrepancy arises from the different methods of rejection of interlopers, Bird's method being much less sophisticated and less efficient that the methods adopted by Escalera et al. and Girardi et al. As a consequence, Bird tended to detect substructures in clusters where Girardi et al. did not, because of the much stronger contamination by interlopers, that Bird considered as members of the main system along the l.o.s. In other words, this is a typical case of contamination of the substructure analysis by projection effects. As a matter of fact, also Bird found that the effect of substructure is much reduced when only the central part of the cluster is considered (thus effectively reducing the influence of projection effects).

The limited effect of substructure on the mass estimates in the majority of clusters found by Escalera et al. (1994) and Girardi et al. (1997a) was confirmed in the cosmological simulations of Tormen et al. (1998), and Brainerd et al. (1999). Similarly, Xu et al. (2000) showed that, while the internal structure of a cluster may depart from dynamical relaxation, some statistical properties of clusters are approximately the same as for virialized systems (the "quasi–virialization" scenario). The mass estimates of groups were also found to be robust against the influence of substructures by Zabludoff & Mulchaey (1998).

The accretion of subclusters from the projected filaments along the l.o.s. (see § 5.1) could lead to overestimate a cluster velocity dispersion even before the merger event occurs. A detailed dynamical and structural analysis of the cluster and its surrounding LSS is needed to identify the accreting groups and projected filaments and return a reliable cluster velocity dispersion estimate (see, e.g., the case of ABCG 1689, Girardi et al. 1997b; Centaurus, Churazov et al. 1999; and, in particular, ABCG 85, Durret et al. 1998).

Apart from the effects on the velocity dispersion of a cluster, substructures have a more general influence on the global distribution of cluster galaxy velocities and positions. The velocity distribution of galaxies within a subcluster can be displaced with respect to the mean velocity of the cluster (Zabludoff & Franx 1993; Scodeggio et al. 1995; Quintana et al. 1996). Zabludoff & Franx (1993) argued that such asymmetries in the velocity distribution last until the subclusters merge with the central cluster. Substructures therefore produce asymmetries in the velocity distribution, precluding a reliable determination of the galaxy orbits based on the shape of the velocity distribution profile (Merritt 1987).

The effect of cluster substructures is evident in the velocity vs. clustercentric radius (R, v) distribution for cluster galaxies. The theory of spherical infall predicts the existence of caustics of infinite galaxy density in the (R, v)–space, but substructures make a substantial contribution to the amplitude of the caustics, which are related to the escape velocity from the cluster (Rines et al. 2000). When averaging over many clusters, the velocity asymmetries are largely erased, but galaxies in subclusters still have a different (R, v)–distribution from galaxies outside substructures (Biviano et al. 2001).

A dynamical consequence of an off–axis cluster merger is the transfer of the angular momentum of the infalling subcluster to the system. Roettiger & Flores (2000) found that the transfer of angular momentum is more efficient towards the collisional component (the intra–cluster gas), and this can explain the velocity gradient in the intra–cluster gas of Perseus (Dupke & Bregman 2001). On the other hand, the simulations of Caldwell & Rose (1997), Lima Neto & Baier (1997), and Gomez et al. (2000) all found that significant angular momentum is also transferred to the galaxy component, resulting in a velocity gradient of the galaxy population. Apart from the obvious cases of bimodal clusters, only few clusters show a significant velocity gradient and the relative correction to the global value of velocity dispersion is very small (some tens of km s^{-1}, Girardi et al. 1996). In Coma, Biviano et al. (1996) and Colless & Dunn (1996) provided evidence for a significant velocity gradient in the core region. Of course, a technical problem in these studies is that only the l.o.s. component of the velocity tensor is observable.

Even more extreme are the consequences of merging on the velocity distribution of the members of the accreting clump. In particular, it is expected that tidal stripping affects more strongly the less bound galaxies in the group, so that the groups tend to develop truncated velocity distributions (see Gurzadyan & Mazure 1998, 2001).

The effects of substructures on the projected distribution of cluster members are less important than the effects on their kinematics (but see Bird 1995 for a different opinion). However, it has been suggested that fictitious cores in the cluster galaxy distribution can be produced by the presence of subclusters in the central cluster regions (Fitchett & Webster 1987; Mohr et al. 1996). Roettiger et al.'s (1993) simulations showed that as a consequence of a cluster–subcluster merger, the cluster core is elongated by 10% in the direction perpendicular to the merger axis, and by 30% in the direction parallel to the merger axis. Several simulations and observations indicated that the elongation of a cluster is induced by the accretion of groups along filaments (e.g., Roettiger et al. 1997; Durret et al. 1998; see § 5.1).

It is interesting to compare the mass obtained from the virial analysis of the galaxy distribution, with those inferred from X–ray and gravitational lensing analyses. In fact, the two former methods assume that the cluster is in dynamical equilibrium, while the latter only requires some assumption about the geometry of the cluster, so that a discrepant result could be a signature of the presence of substructure. If a cluster is out of equilibrium, the optical and X–ray analyses can lead to serious discrepancies.

Observationally, optical and X–ray subclustering are generally well correlated (Kolokotronis et al. 2001, but see Baier et al. 1996), but in a few individual cases the galaxies and the IC gas have different distributions, and the peak of the X–ray surface brightness does not coincide with the peak of the galaxy distribution (Zabludoff & Zaritsky 1995: ABCG 754; Barrena et al. 2001: 1E 0657 – 56).

Indeed, numerical simulations have shown that the galaxies and the IC gas react on different time scales during a merger, e.g. two clusters can pass through one another without destroying the individual optical components, while the gas is strongly affected (e.g., White & Fabian 1995; Roettiger et al. 1997). The shocks from the infalling subcluster create temperature and density gradients that can lead to an overestimation of the mass determined assuming hydrostatic equilibrium for the X–ray emitting gas, by up to a factor 2 (e.g., Schindler 2000). On the other hand, substructures also flatten the density profile and this could lead to a mass underestimation, by a similar factor. According to Roettiger et al.'s (1997) hydro/N–body simulations, much of the heating of the merger goes into energy of the IC gas, while heating of the dark matter component is minimal, and the dark matter component can efficiently redistribute energy through violent relaxation. On the other hand, Lewis et al. (1999) suggested that merging affects the optical estimates of a cluster mass much more than the X–ray estimates mainly because of the different nature of measurements, which, in the optical case, have the added difficulty of determining the interlopers. Lewis et al. also pointed out that substructure could boost the lensing (in particular strong lensing) mass estimates up, by a factor 1.6. King & Schneider (2001) found that substructures increases the dispersion of all recovered parameters from weak lensing technique. It is therefore difficult to predict *a priori* which kind of mass estimate is more reliable.

Several discrepancies in the mass estimates from the different methods were pointed out in the past (e.g., Miralda–Escudé & Babul 1995; Smail et al. 1997; Wu & Fang 1997). Recent results have suggested that, when clear bimodal clusters are culled from the sample, the mass estimates from the three methods are in reasonable agreement, except perhaps for the central cluster regions, possibly because of the effect of small–size substructures (see, e.g., Allen 1998; Girardi et al. 1997b, 1998; Lewis et al. 1999). More difficult remains however the task of correctly estimating the masses of subclusters, which are even more affected by the merger process than the main cluster (see, e.g., the case of the NGC4839 group in Coma – Colless & Dunn 1996 vs. Neumann et al. 2001).

Other global cluster properties are affected by the presence of substructures. This is particularly evident when considering the X–ray vs. optical properties, since these are affected in different ways, due to the collisional nature of the IC gas and the non–collisional nature of the cluster galaxies. Substructure has been invoked to explain observed departures from the L_X–σ_v relation (e.g., for ABCG 1060, Fitchett 1988a), and from the σ_v–T_X relation. High values of $\beta_{spec} = \sigma_v^2/(kT_X/\mu m_p)$ (where μ and m_p are, respectively, the molecular weight and the proton mass) are suggestive of the presence of substructure since $\beta_{spec} \sim 1$ if only gravitational processes are important (e.g., Edge & Stewart 1991), but also anomalously low values of β_{spec} have been found in merging clusters (e.g., in ABCG 754, Girardi et al. 1996). The value of β_{spec} can thus provide useful insight into the evolutionary stage of a merger (e.g., Bird et al. 1995; Shibata et al. 2001). On the other hand, both the velocity dispersion and the X–ray temperature of a cluster tend to increase during a merger, so that there is a chance to observe $\beta_{spec} \simeq 1$ also for non–relaxed clusters.

5. SUBSTRUCTURE AND COSMOLOGY

5.1. ACCRETION FROM THE LSS

In hierarchical clustering cosmological scenarios clusters of galaxies form by the accretion of subunits. Numerical simulations show that clusters form preferentially through anisotropic accretion of subclusters along large scale filaments (West et al. 1991; Katz & White 1993; Cen & Ostriker 1994; Colberg et al. 1998, 1999). The infall of matter onto clusters arises from clumpy, inhomogeneous, filaments and sheets (Colberg et al. 1999). The signature of this anisotropic cluster formation is the cluster elongation along the main accretion filament (e.g., Roettiger et al. 1997). This is certainly true for the collisionless component, while the IC gas is first elongated similarly, and then is pushed outwards perpendicular to the merger axis (e.g., Schindler 2000).

There is a wealth of observational data supporting the anisotropic cluster formation scenario borne out by numerical simulations. The LSS topology is characterized by large filamentary structures (e.g., the Perseus–Pisces supercluster, described by Haynes & Giovanelli 1986, and the Great Wall, described by Geller & Huchra 1990). The cluster main axes are oriented along the main directions of the surrounding LSS (Gregory & Thompson 1978; Binggeli 1982; Fontanelli 1984; Rhee et al. 1992; Plionis 1994; West et al. 1995; Dantas et al. 1997; Bardelli et al. 2001). Zabludoff & Franx (1993; see also Neill et al. 2001) showed that galaxies of different morphological types have different mean velocities in some clusters, and interpreted this as evidence for anisotropic accretion of clumps of (mostly) spirals onto these clusters.

Several detailed studies have recently added further evidence for the infall of groups into clusters along preferential directions. Girardi et al. (1997b) showed that ABCG 1689 is composed of two main structures aligned along the l.o.s., that add to three small foreground groups already identified by Teague et al. (1990). The ABCG 85/87/89 complex analyzed by Durret et al. (1998) is one of the most striking examples of structure alignments (see Fig. 1.7). Using both optical and X–ray data, these authors showed that ABCG 89 is a l.o.s. superposition of two groups which are located in intersecting sheets on opposite sides of a large galaxy bubble. ABCG 87 is resolved into individual groups, organized as a filament almost perpendicular to the plane of the sky, possibly falling onto ABCG 85. Remarkably, the alignment goes from small to very large scales: the ABCG 85/87 filament is coaligned both with the cD galaxy of ABCG 85 and with a structure that extends over more than 5 degrees on the sky (corresponding to 28 Mpc at the redshift of ABCG 85), and which includes ABCG 70, 85, 89, 87, 91 and some other groups. A strongly supporting evidence for the formation of rich clusters at the intersection of filaments has come from the study of Arnaud et al. (2000). They identified in ABCG 521 a young cluster in formation at the crossing of two filaments, one pointing towards ABCG 517 and the other in the direction of ABCG 528/518 (see Fig. 1.8). They splitted ABCG 521 into a main structure, ABCG 521S, onto which a smaller group, ABCG 521N, is infalling.

West & Blakeslee (2000) have been able to determine the principal axis of the Virgo cluster in 3D, by determining galaxy distances with the surface–brightness fluctuations method. This axis joins a filamen-

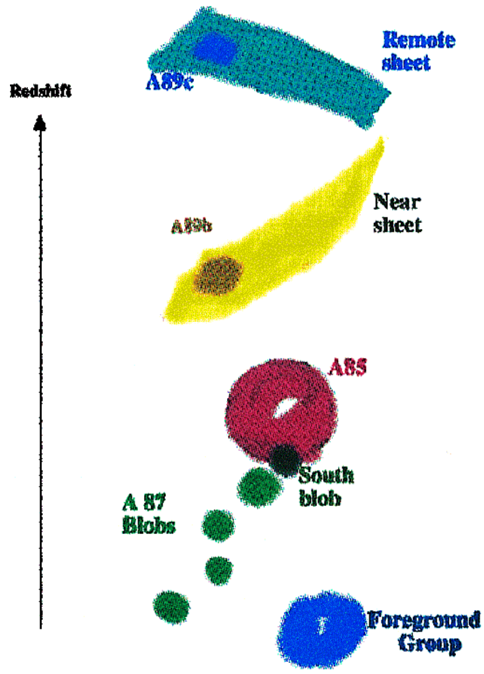

Figure 1.7. An artist's view of the ABCG 85/87/89 complex. Taken from Durret et al. (1998).

tary bridge of galaxies connecting Virgo to ABCG 1367. The Virgo ellipticals themselves have their axes aligned along this same direction. Since the Coma cluster is also embedded in the LSS at the intersection of filaments pointing to other clusters, and, in particular, to ABCG 1367, Virgo and Coma are themselves connected (West 1998). West (1998) also presented evidence that the distribution of groups around Coma (from Ramella et al. 1997) is suggestive of future infall onto the cluster along the same direction traced by Coma galaxies. Finally, direct evidence that the LSS filaments are clumpy has come from weak lensing analyses (Clowe et al. 2000). Rich superclusters of galaxies are the ideal environment for studying major cluster mergers. In fact, the high local overdensity of the superclusters implies higher relative velocities for clusters, and therefore increases the cross–section for cluster–cluster collisions (Bardelli et al. 2001). Most remarkable is the central region of the Shapley Concentration, where three rich clusters (ABCG 3556, 3558, and 3562) and several poor clusters or groups are aligned. Bardelli and collaborators have described the properties of this complex in a series of papers. In particular, for what concerns the optical analysis of sub-

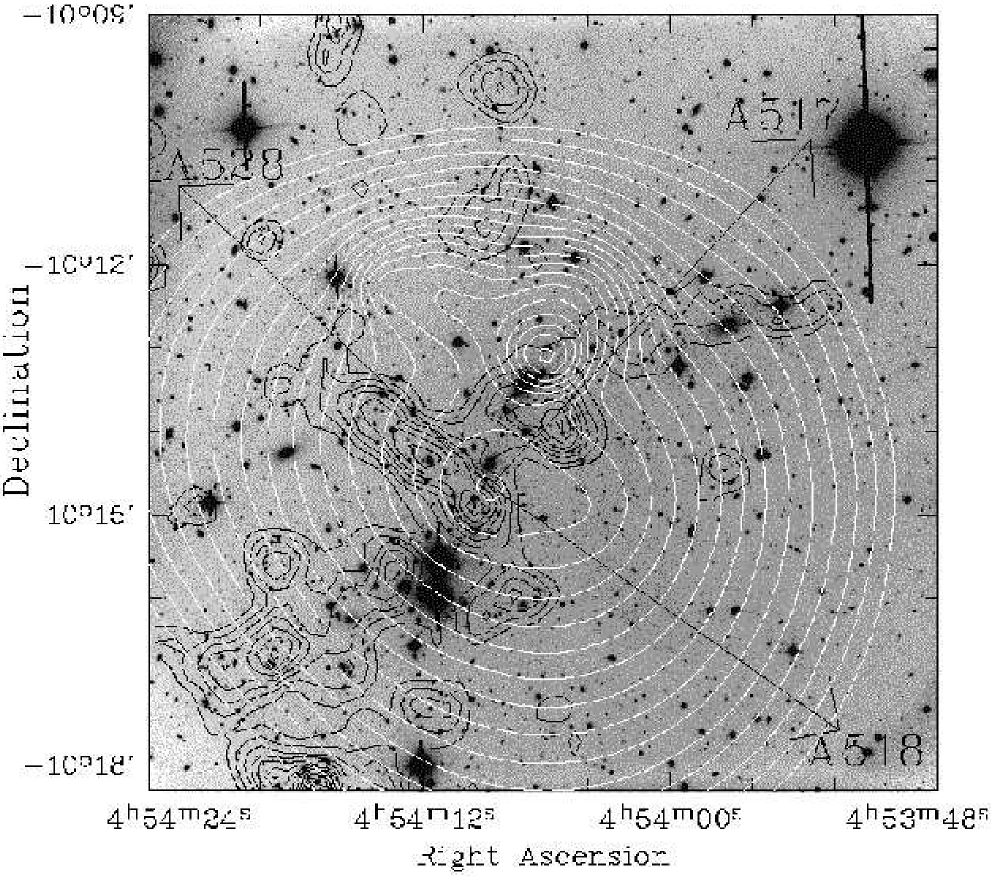

Figure 1.8. Galaxy isodensity contours in black, and X–ray isointensity contours in white, are superimposed on the V–band image. The direction towards the clusters ABCG 517, ABCG 528, and ABCG 518 are also indicated. Taken from Arnaud et al. (2000).

structures, Bardelli et al. (1998a) used *Dedica* (Pisani 1996) to identify a large number of substructures and drew two alternative scenarios for the structure and dynamical evolution of this cluster complex (see Fig. 1.9). In one scenario, the core of the Shapley Concentration would correspond to a cluster–cluster collision seen just after the first core passage. In the alternative scenario, this structure would result from a series of incoherent group–group and cluster–group merging. A similar study – but using *KMM* instead of *Dedica* – has been performed by Barmby & Huchra (1998) in the Hercules Supercluster.

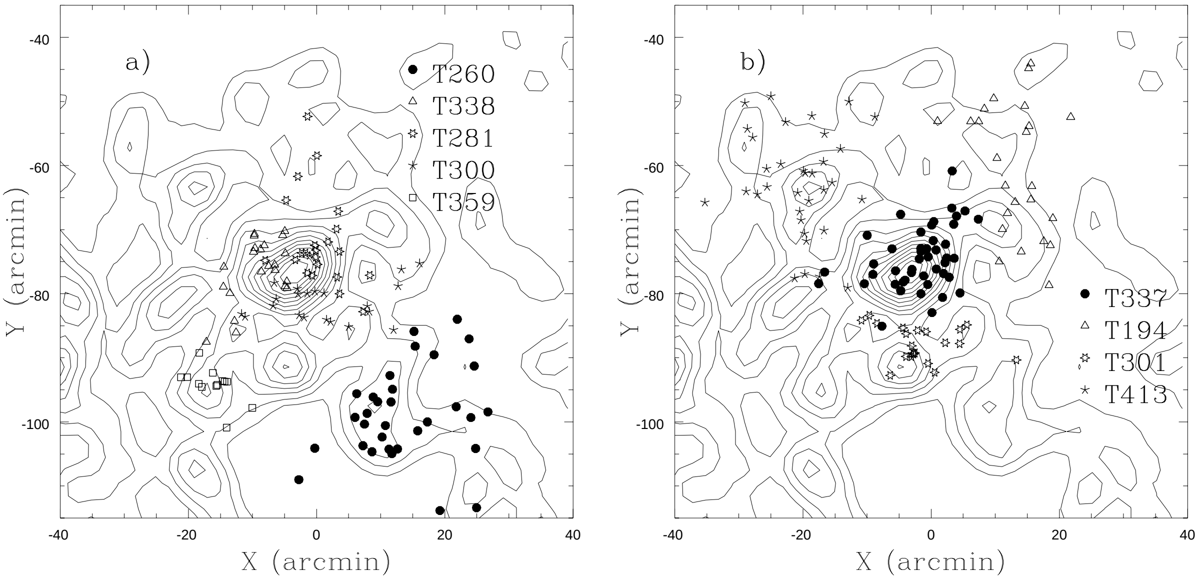

Figure 1.9. Groups found in the ABCG 3558 cluster region. The positions of sub–cluster galaxies found by using *3D Dedica* (Pisani 1996) are overplotted onto the smoothed 2D isodensity contours. Different symbols label galaxies in different groups. For clearness the group members are splitted in two panels. Taken from Bardelli et al. (1998a).

5.2. ESTIMATING Ω

Since the frequency of subclustering at the present epoch is set by the mean density at recombination, substructure analyses in clusters can be used to constrain Ω_M with little influence from Ω_Λ (Richstone et al. 1992; Lacey & Cole 1994; Thomas et al. 1998). In fact, in a low density Universe the structure formation tends to freeze at $z = 1/\Omega_M$ (e.g., Mamon 1996), while in a high density Universe clusters accrete 50% of their mass in the last 5–8 Gyr (Brainerd et al. 1998). From the observed degree of subclustering, Richstone et al. (1992) concluded that a high density Universe was implied, unless substructures can survive longer than expected, or projected groups along the l.o.s. are mistaken for subclusters.

Following analyses produced contradictory results. Late results of cosmological simulations have suggested that low–density models are able to produce a fraction of clusters with substructure in substantial agreement with the observations when proper account is taken for projection effects and the (in)efficiencies of substructure–detection methods

(Jing et al. 1995; Jing & Borner 1996; Cen 1997; Knebe & Müller 2000). Dutta (1995) suggested that at least 500 galaxies per clusters are needed for discriminating between low and high Ω_M universes, by using the Δ–*statistics* test, although Knebe & Müller (2000) provided a more optimistic estimate. In general, however, it is the dark matter component, and not the galaxies, which are traced by cosmological simulations, and this complicates the direct comparisons with observations.

The main unknown in this approach is the survival time of the substructure within a cluster. If substructures are long–lived, a high fraction of clusters with substructure can be reconciled with a low–density Universe. Bimodal configurations, and off–axis mergers, in particular, can last long (Cavaliere et al. 1986; Cavaliere & Colafrancesco 1990; Roettiger & Flores 2000), up to 4 Gyr (Nakamura et al. 1995). The compactness of the infalling groups helps them to survive for a significant fraction of the Hubble time (Tormen et al. 1998). Since hierarchical clustering predicts smaller systems to be more compact, Tormen et al. suggested a longer survival time for smaller groups, while the large groups rapidly sink into the cluster centre and lose their identity. On the other hand, González–Casado et al. (1993, 1994) suggested that the longest lasting subclusters are detached cores of colliding clusters. In general, several investigations have agreed that the presence of subclustering significantly slows down the collapse and virialization of a cluster (Cavaliere et al. 1986; Thomas & Couchman 1992; Schindler & Böhringer 1993; Antonuccio–Delogu & Colafrancesco 1994; Roettiger et al. 1998) with respect to the classical homogeneous spherical infall model of Gunn & Gott (1972).

Possibly, a more interesting approach comes from the comparison of the dynamical status of nearby and distant clusters. In particular, there is a growing evidence that distant clusters (at $z > 0.8$) display a young dynamical state. Smail et al. (1997) presented weak lensing results for 12 distant clusters and explained their high velocity dispersions as overestimates induced by subclustering. Lubin et al. (1998) showed that the cluster Cl 0023+0423 at $z = 0.84$ is a candidate ongoing merger of two low–dispersion groups. Both RX $J1716.6 + 6708$ at $z = 0.81$ and MS $1054 - 03$ at $z = 0.83$ have a filamentary morphology, which is suggestive of a young dynamical status (Gioia et al. 1999, see Fig. 1.10; van Dokkum et al. 2000), and the former of the two has a β_{spec} in excess of one, indicative of an ongoing merger (see § 4). Several distant clusters have been found to have companions (e.g., the supercluster at $z = 0.91$ found by Lubin et al. 2000, and the two clusters at $z = 1.26$ found by Rosati et al. 1999). Analyses of the environment around distant quasars and radio–galaxies have also indicated the presence of

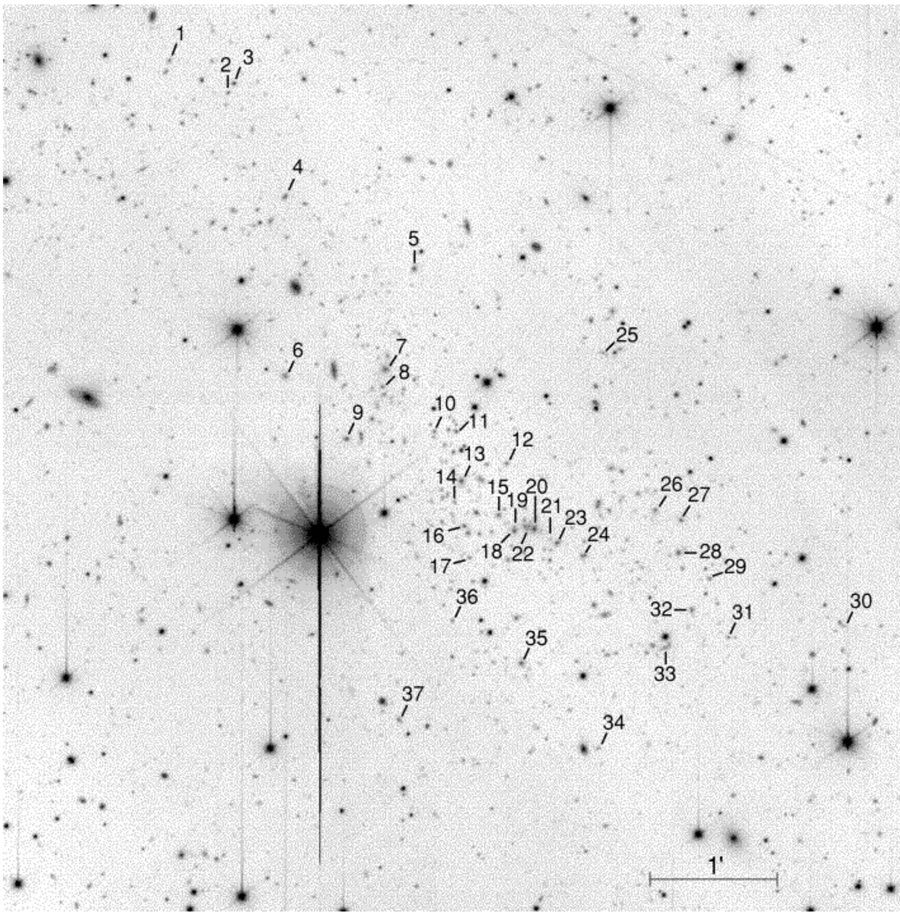

Figure 1.10. The I–band image of $RXJ1716.6 + 6708$. The cluster galaxies are marked and show the filamentary morphology of this cluster. Taken from Gioia et al. (1999).

subclustering. In particular, the study of the $104420.8 + 055739$ quasar at $z = 1.23$ suggested the presence of a merger among two compact groups (Haines et al. 2001, see Fig. 1.11). Pentericci et al. (2000) found a structure in the Lyα emitters around a radio–galaxy at $z = 2.16$, that they splitted into two groups with velocity dispersions of 530 and 280 km s^{-1}. By approaching the epoch of cluster formation, it will be possible to follow the evolution of clustering and set useful constrain on cosmological models.

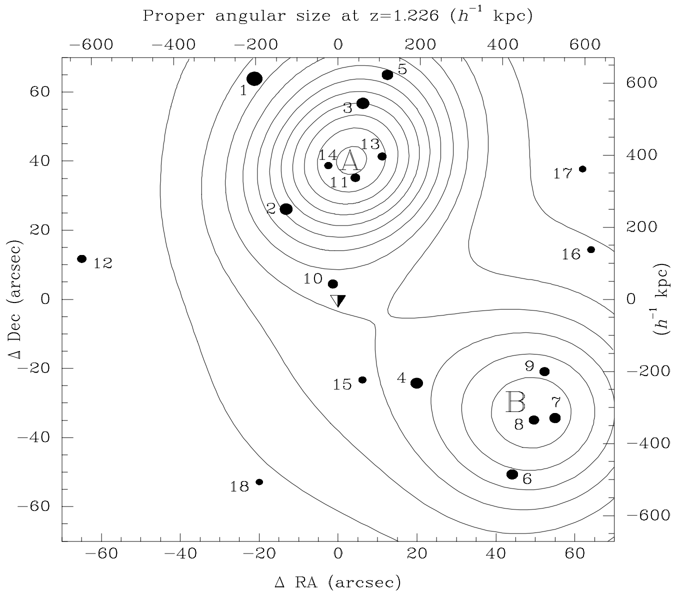

Figure 1.11. Isodensity contours of the red galaxies (dots) in the field of quasar 104420.8 + 055739 (triangle). The galaxies are numbered in order of increasing K magnitude. Taken from Haines et al. (2001).

6. CLUSTER MERGERS AND GALAXY PROPERTIES

6.1. BRIGHTEST CLUSTER MEMBERS

Cluster mergers are intimately connected with the properties of cluster galaxies. We start by considering the brightest cluster members (BCMs in the following). Their abnormal luminosities have long been thought to result from repeated galaxy merging and cannibalism (e.g., Hausman & Ostriker 1978; Bhavsar & Barrow 1985; but see Merritt 1984). The fact that larger BCMs are found in higher density environments, suggests the growth of these galaxies is governed by their local environment (within 400 kpc; see Fisher et al. 1995).

Both Hill et al. (1988) and Sharples et al. (1988; see also Malumuth 1992) argued that BCMs form in groups via merging of smaller galaxies, before the cluster virialization effectively renders merging impossible (because of the high velocity dispersion of cluster galaxies). While most BCMs are located very close to the centre of parent clusters (e.g., Adami et al. 1998; Adami & Ulmer 2000), several observations have identified BCMs displaced from the cluster centre, sitting at the bottom of local potential wells. Examples include the three BCMs in Coma (Biviano et al. 1996; Colless & Dunn 1996), the cD in ABCG 2634 (Pinkney et al. 1993), the cD in ABCG 754 (Zabludoff & Zaritsky 1995), the cD in ABCG 2670 (Bird 1994a), the three BCMs in ABCG 521 (Maurogordato et al. 2000), and the extensive analysis of several BCMs by Kriessler & Beers (1997). The merger of the BCM host group with the cluster naturally produces a velocity offset of the BCM with respect to the cluster, until dynamical friction puts the BCM at rest at the bottom of the cluster potential (see, e.g., Pinkney et al. 1993). In general, first observational results have overestimated the number of BCMs with significant different velocities from the cluster mean, but a significant number of BCMs with velocity offsets persist (Beers et al. 1991; Gebhardt & Beers 1991; Bird 1994b). These offsets could be partly produced by an oscillatory motion of the BCM around the bottom of the cluster potential (Lazzati & Chincarini 1998), and partly by gravitational redshift (Cappi 1995). However, the global observational evidence is suggestive of the formation of at least some BCMs in groups which later infall onto clusters. Consistently, Beers et al. (1991) found that only in clusters with independent evidence for substructure, do the BCMs have a significant velocity offset.

Whether the BCM retains its original galaxy group or not while approaching the cluster centre is debatable. Evidence for bound populations around some BCMs has been provided by observations of local overdensities of galaxies around the BCM with a velocity dispersion lower than that of the host cluster. Subclusters around BCMs were detected in e.g. the core of the Coma cluster (see Biviano et al. 1996 and references therein), ABCG 2634 (Bothun & Schombert 1990), ABCG 496 (Quintana & Ramírez 1990), but most BCMs are *not* accompanied by a bound population of satellite galaxies (e.g., Bower et al. 1988; Gebhardt & Beers 1991; Merrifield & Kent 1991).

There is strong observational evidence for the alignment of the BCM major axis with the major axis of its cluster and the surrounding LSS (e.g., Binggeli 1982; Lambas et al. 1990; Johnstone et al. 1991; Rhee et al. 1992; Dantas et al. 1997; Durret et al. 1998). This fact is difficult to explain if the formation of the BCM is totally uncorrelated to the cluster formation. According to the simulations of Rhee & Roos (1990), West (1994b) and Dubinski (1998), the alignment effect is explained by the formation of BCMs through the merging of several massive galaxies accreted along a filament early in the cluster history. This scenario can also account for the correlation of the BCM and cluster properties (Edge 1991).

An alternative scenario for the formation of BCMs is the coalescence of the central brightest galaxies of merging subclusters (Johnstone et al. 1991). Since groups infall onto clusters along filaments defined by the surrounding LSS, this scenario can also naturally account for the observed axes alignments. Within this scenario it is easy to explain the distorted morphology of the cD galaxy in ABCG 697 (Metzger & Ma 2000), as well as the multiple nuclei of some BCMs, in terms of ongoing mergers of the brightest galaxies of individual subgroups (Tremaine 1990). The high relative speed of the galaxies making up a dumbbell galaxy may be the result of the orbital motions of their subclusters within the cluster (Beers et al. 1992). It is remarkable that dumbbell dominant galaxies are often found in clusters with a significant degree of subclustering (e.g.: ABCG 3530 and 3532 in the Shapley concentration, see Bardelli et al. 2001; ABCG 521, see Maurogordato et al. 2000; ABCG 3266, see Quintana et al. 1996). As argued by Merritt (1984), accretion of galaxies onto the central BCM of a cluster is not easy, because of the high velocity dispersion of cluster galaxies, but when two clusters merge, the two cluster BCMs rapidly sink to the bottom of the common potential well, because of dynamical friction (Valentijn & Casertano 1988). It takes several Gyr for the two BCMs to merge (Rix & White 1989; Cavaliere & Colafrancesco 1990) and therefore many dumbbell galaxies can be observed. Note, however, that the observed number of multiple–nuclei BCMs is boosted up by projection effects (see, e.g., Hoessel & Schneider 1985; Blakeslee & Tonry 1992; Gregorini et al. 1992).

If groups are the site of BCM formation, significant dynamical evolution has occurred in them prior to their infall onto the cluster core. Significant luminosity segregation could then be expected, with the most massive galaxies forming a dense core, surrounded by fainter galaxies. When the groups enter the cluster, they are tidally truncated, and the less bound population of faint galaxies is dispersed throughout the cluster, while the detached core maintains its identity for several crossing times (see also González–Casado et al. 1994; Tormen et al. 1998; Balogh et al. 2000). This scenario would account for the observations of Biviano et al. (1996) who showed that substructures in the Coma cluster core are better traced by the bright galaxy populations, while faint galaxies have a much smoother distribution. The same is true in Virgo, where dE's and dS0's describe a smoother distribution than bright galaxies, which instead are sub–clustered around the brightest galaxies (see Fig.3 of Schindler et al. 1999).

6.2. GALAXY STAR–FORMATION

Recent results from numerical simulations have shown that cluster mergers can influence the evolution of the cluster galaxy population.

Bekki's (1999) simulations showed that mergers induce a time–dependent gravitational field that stimulates non–axisymmetric perturbations in disk galaxies, leading to starbursts (SBs in the following) in the central parts of these galaxies. Gnedin (1999) showed that the infall of groups onto a cluster induces a temporal variation of the cluster gravitational potential, as well as shocks, that enhance the galaxy–galaxy interactions, and produce SB in gas–rich infalling galaxies. After collision, the SB (or post–starburst, PSB in the following) galaxies would remain well outside the cluster, and near the developed substructure for a few Gyr. Moore et al. (1999) found that low–surface brightness galaxies evolve dramatically as a result of rapid encounters with substructures and strong tidal shocks. Similar results are found in the simulations of Dubinski (1999).

In their numerical SPH simulations, Fujita et al. (1999) found that cluster mergers suppress, rather than trigger, star formation in galaxies, because of increasing ram pressure during cluster–cluster collisions. However, before stripping, the formation activity *is increased,* but for a short period (≤ 0.4 Gyr). A more detailed description of the full process of ram–pressure stripping during cluster–cluster mergers is given by Roettiger et al.'s (1996) simulations. They showed that a bow shock forms on the leading edge of an infalling subcluster, that effectively reduces the ram pressure, and protects the gas–rich subcluster galaxies. This protection fails at core crossing, and galaxies passing through the shock initiate a burst of star formation, followed by rapid stripping. Similarly, Tomita et al. (1996) argued that in a merging cluster there are regions overdense in IC gas, and some galaxies may experience a rapid increase of external pressure, leading to compression of molecular clouds and SB. An excess of star–forming galaxies is therefore expected in the region between two colliding subclusters.

The first observational evidence for a correlation between cluster mergers and star formation activity in cluster galaxies has come from the observations of the Coma cluster. As shown by Biviano et al. (1996), Coma is currently undergoing accretion of several groups (centred on the bright galaxies NGC 4874, 4889, 4839, 4911), and can therefore be suspected to host significant merger–induced activity. Strong Balmer absorption, consistent with a PSB phase of star formation, was first detected in disk galaxies in Coma by Bothun & Dressler (1986). In the Coma centre most bright galaxies have uniform old ages (Bower et al. 1990, 1992; Rose et al. 1994) while the age–range among brighter galax-

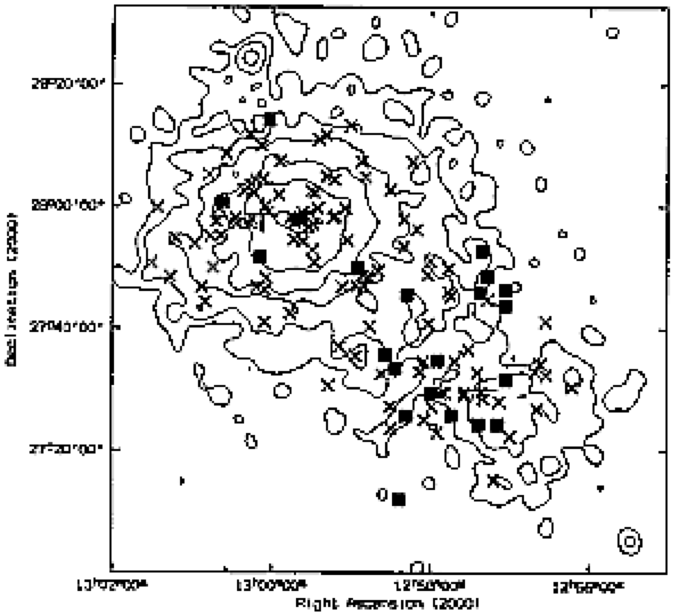

Figure 1.12. Positions of spectroscopically observed galaxies in Coma overlaid on the ROSAT X–ray isocontours. Abnormal–spectrum galaxies are denoted by filled squares. Taken from Caldwell et al. (1993).

ies in the SW Coma region close to the subcluster around NGC 4839 was found to be large by Caldwell & Rose (1998). Caldwell et al. (1993) found that 30% of the early–type galaxies in SW Coma concentration have enhanced Balmer absorption lines or even emission lines. Similar abnormal spectrum early–type galaxies are found scattered all around Coma (Caldwell & Rose 1997) but the excess of this kind of galaxies in the SW region is remarkable (see Fig. 1.12). The spectral features are indicative of a SB which ceased 1 Gyr ago (Caldwell et al. 1996). The disky morphology of PSB galaxies in Coma indicates that, whatever the mechanism inducing the SB, it mainly affects the internal gas rather than the structure of these galaxies (Caldwell et al. 1999). Learning from the results of the numerical simulations, the most straightforward interpretation of this excess is that of an induced SB activity – followed by a PSB phase – in galaxies located along the merger axis of the NGC 4839 group with Coma. Since these galaxies are mainly located near the subcluster, but not exclusively, it is likely that core–crossing has already occurred.

Caldwell & Rose (1997) found abnormal–spectrum early–type galaxies in many other clusters, all with substructures. Although not always located close to the substructures, these galaxies are often found in the tails of the cluster velocity distribution. In Coma the abnormal–spectrum galaxies are mostly in a PSB phase, but there are clusters (e.g., $DC0326-53/0329-52$) where most abnormal–spectrum early–type galaxies are star–forming, possibly indicating that the merger is in an earlier phase. Similarly, Drinkwater et al. (2001) speculated that the high fraction of SB galaxies in the SW group of Fornax indicates that this group has not yet crossed the cluster core.

According to Moss & Whittle (2000) SB galaxies are found mostly in the richest clusters with substructure. They identified the mechanism responsible for the SB phase in subcluster merging, and suggest this as a plausible explanation for the lack of the morphology–density relation in irregular clusters at intermediate redshift (Dressler et al. 1997). The increased star formation activity of galaxies in substructured, vs. relaxed, clusters was also found in clusters from the ENACS collaboration (Biviano et al. 1997), and in a sample of distant clusters analysed by Wang & Ulmer (1997). Clusters from the CNOC collaboration (e.g., Yee et al. 1996) are found to have a lower fraction of PSB and SB galaxies than clusters from the MORPHS collaboration (Dressler et al. 1997). A possible explanation of this difference is that MORPHS clusters are generally more substructured than CNOC clusters (which are all X–ray selected), and the presence of substructures enhances the frequency of SB (Ellingson et al. 2001).

It is not certain that the interaction with the cluster environment is essential for the formation of SB and PSB galaxies. According to Hashimoto et al. (1998), in groups or poor clusters the level of normal star formation and starburst is higher than in rich clusters and the field, in clear disagreement with Moss & Whittle (2000). Zabludoff et al. (1996) and Ellingson et al. (2001) argued that galaxy–galaxy interactions and mergers happen more frequently in groups (because of their lower velocity dispersion). In clusters with substructures the number of recently accreted groups is higher, and this would naturally explain the higher fraction of "cluster" galaxies in a SB or PSB phase. Consistently, the high fraction of ongoing mergers in the distant rich cluster MS $1054-03$ is mainly located in small infalling groups (van Dokkum et al. 1999).

Nevertheless, this scenario can hardly explain the excess of these galaxies in the region *between* two merging groups. For example, the bluest galaxies in the complex ABCG 3558/3562 are found in the region between the two colliding clusters (Bardelli et al. 1998a), and the emission–line galaxies in ABCG 3266 are mainly located on one side of the cluster, tracing the direction of a subclump crossing the cluster core (Flores et al. 2000). Similarly, Abraham et al. (1996) found that [OII] emitters in ABCG 2390 have a spatial and velocity distribution which is related to infall pattern of the NW group, which is itself populated mostly by red evolved galaxies. Moreover, if infalling groups are originally composed of star–forming galaxies, these galaxies must suffer a morphological modification in order to account for the observed morphological fractions of galaxy samples in substructures (Beers et al. 1992; Biviano et al. 2001). Possibly, both near–neighbour interaction and the tidal field of the cluster play a significant role in triggering star formation (Moss et al. 1998).

The ram–pressure stripping of cluster galaxies is probably also responsible for their HI–deficiency. There are several cases in which the HI–deficient galaxies are found to have an anisotropic spatial distribution, tracing the motions of infalling groups (e.g., Bravo–Alfaro et al. 2000; Chengalur et al. 2001; Solanes et al. 2001). When these groups pass through the cluster core, their densest part can survive the collision, but they leave behind a trail of gas–deficient galaxies (Solanes et al. 2001). Possibly related to the same phenomenon are the deficiency of radio–galaxies in substructured clusters (in Coma, see Kim et al. 1994; in Shapley, see Venturi et al. 2000; Bardelli et al. 2001), and the presence of narrow–angle tail radio–galaxies, where the radio–jet is probably bent by the bulk motion of the IC gas, triggered by the cluster–cluster merger (Bliton et al. 1998; Burns 1998).

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