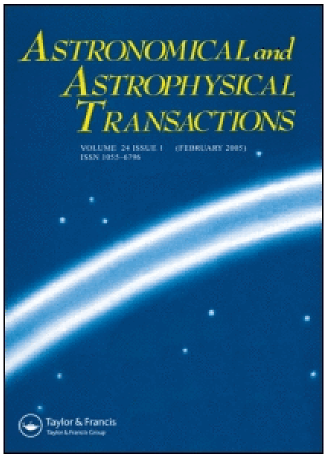

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SUBCLUSTERING AND COOLING FLOW IN ABELL CLUSTERS OF GALAXIES

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Correlation between the subclustering determined through the application of the wavelet analysis to the optical data and existence of cooling flows observed in the X-ray range are studied. On the basis of eight galaxy clusters with cooling flow and nine non-cooling objects it is shown that substructures are observed in both groups.

Keywords: Individual clusters of galaxies; Properties

1 INTRODUCTION

Clusters of galaxies are the most massive, gravitationally bound systems known in the Universe. Their masses can be of the order of 5×10^{14} solar masses. Their structure is much more complicated than was thought half a century ago. Then, galaxy clusters were regarded as a collection of gravitationally interacting objects which can be approximated as mass points. Now, we know that these are very complex systems, containing hot intracluster gas with $kT \approx 5\,\mathrm{keV}$ and the electron density $n_e \approx 10^{-3}\,\mathrm{cm}^{-3}$. This gas is the source of emission also in X-rays through free–free radiation. Its X-ray luminosity is about $10^{44}\,\mathrm{erg\,s}^{-1}$.

The presence or absence of substructures in clusters of galaxies is important for the study of their formation, evolution and dynamics. The existence of subclustering suggests that clusters are young objects. The properties of galaxies in clusters depend on their environment. In clusters, morphology segregation is found among galaxies both in substructures and outside them (Biviano *et al.*, 2002). Similar results based on the Automated Plate Measuring Galaxy Survey (APM) cluster sample were obtained by Plionis (2001). Moreover, he found that dynamically young clusters are much more clustered spatially in the analysed sample of data. Kolokotronis *et al.* (2001) investigated a sample of 22 rich galaxy clusters, finding strong correlation between the optical (APM) and X-ray Röntgenstrahen Satellite (ROSAT) morphological parameters. Their work led to the conclusion that in both parts of

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the spectrum it is possible to identify the dynamic state of a cluster correctly. Cluster ellipticity is correlated with red shift; it increases with increasing red shift for the investigated sample with $z < 0.18$ (Plionis, 2002). All these investigation show that galaxy clusters are complex evolving structures, in which dynamic effects are observed.

From the viewpoint of X-ray data the existence of cooling flows in some objects is very interesting. In the central region of a cluster, a huge concentration of hot gas is observed. It is bounded by the cluster potential. At the centre of the cluster there is a smaller cooler cloud of gas. The existence of this cool region constitutes observational evidence of the existence of cooling flows. When the gas density at the centre is high, the radiative loss of energy due to the X-ray emission influences gas parameters significantly. During radiation, the gas temperature and pressure decrease owing to the energy loss. The compression of gas by gravitational force and the hotter surrounding gas takes place. So, the density of gas increases, causing further radiation. The process continues until the condensation of gas has formed filaments. This motion of the gas located inside the potential well towards the centre is the cooling flow. If the gas density is low, the time of radiation is comparable with the Hubble time but, when it is of the order mentioned above, thermal energy is radiated within about 2 billion years. The increase in gas density shortens the time scale of radiation proportionally, which means that this cooling has an effect on the dynamics of the gas in the cluster. It is accepted that galaxy clusters with a dominant galaxy have greater cooling flows than galaxies without such objects, which suggests the dependence of the cooling flow on the cluster morphology. The aim of this paper is to study the dependence of cooling flow and subclustering. In the present paper, the result of subclustering obtained from two-dimensional data are considered. A comparison of ours and other recent studies indicates a good correspondence between the fraction of substructures detected in two- and three-dimensional data. Thus, the analysis of substructures in clusters of galaxies based on projected, that is two-dimensional, data can reveal a statistically correct percentage of subclustering, disregarding some differences for individual objects (Flin and Krywult, 2002)

The paper is organized in the following manner. Observational data are presented in Section 2, and the method applied, that is the wavelet analysis, is given in Section 3. Section 4 presents the results, while the last section, Section 5, presents our conclusion.

2 OBSERVATIONAL DATA

X-ray data of hot rich galaxy clusters were obtained by the *Beppo–SAX* satellite. In our analysis, we considered 17 Abell clusters, for which both the information on the existence of cooling flow is known (De Grandi and Molendi, 2002) and the subclustering investigated. All optical data come from photographic plates taken with 48 in Schmidt telescopes. The fields containing clusters were scanned. Objects were automatically detected, and their magnitude values computed in many circular apertures, producing a magnitude profile, from which objects were automatically classified as point like or diffuse. Total magnitudes m_T were computed from flux integrated in an aperture of radius $R_1 = 1.5r_1$, where r_1 is the first momentum of intensity distribution (Trèvese *et al.*, 1992). With the above definition, total magnitudes correspond on average to the magnitude m_{iso} computed in a circular aperture determined by the isophote $\mu = 24$ magnitude arcsec^{-2}, with the advantage that r_1 is less noisy than the corresponding isophotal radius (Flin *et al.*, 1995). Magnitude-zero points are taken from literature. The second source of our data is the COSMOS machine. We used the data from the COSMOS–UKST *Southern Sky Object Catalogue*. A wavelet analysis of clusters in this sample has been performed (Krywult *et al.*, 1999). Some other clusters were obtained from the Digital Sky Survey (DSS), with the FOCAS package (Jarvis and Tyson, 1981) to fields extracted from the survey applied (Krywult, 2001).

In the analysis, all galaxies within the radius $R = 1.5$ Mpc ($h = 0.75$; $q = 0.5$) from the cluster centre and with magnitude range from m_3 to $m_3 + 3$, where m_3 is the magnitude of the third brightest galaxy, were considered. For some additional clusters, the result of subclustering investigations performed by Davies and Mushotzky (1993) was accepted.

3 WAVELET ANALYSIS

Detection of structures in the regions under investigation was achieved using the wavelet analysis (Escalera *et al.*, 1994). The wavelet technique is a convolution on a grid of $N \times N$ pixels between the signal $s(r)$ (in our case, the angular positions of galaxies) and the analysing wavelet function $g(r, a)$. In this work, following Escalera and Mazure (1992), we used the two-dimensional radial function called the Mexican hat, given by the formula

$$g(r, a) = \left(2 - \frac{r^2}{a^2}\right) \exp\left(-\frac{r^2}{2a^2}\right), \tag{1}$$

where r is the distance between the position of a galaxy and point (x, y) where the wavelet coefficient is calculated, and a is a scale length for the wavelet used to form the corresponding set of wavelet coefficients. As a result of the convolution, the signal is transformed into a set of wavelet coefficients given by

$$w(r, a) = g(r, a) \otimes s(r). \tag{2}$$

Thus, each pixel in the grid has a corresponding wavelet coefficient. Using a set of different scales a, a structure is detected only when its characteristic size is of the order of the scale applied. Following Daubechies (1990), a factor of $2^{1/2}$ from one scale to another ensures correct sampling in the case of the Mexican hat. When analysed with the largest scale, the field will produce a wavelet image displaying a single central structure. If the scale decreases, the central structure either remains unchanged or splits into substructures. In this way, all structures present on the map were detected, irrespective of their location or size. For the analysis presented here (Fig. 1), the discrete wavelet was computed on a grid of 256×256 pixels for seven scales increasing from $a = 8$ to $a = 64$ (in pixel units), namely 8, 11, 16, 22, 32, 45 and 64 respectively. In order to avoid any edge effects, areas larger than the cluster itself were analysed.

The significance of the substructuring detected using Monte Carlo simulations was modelled. For each cluster and each scale a, the wavelet analysis was carried out on a set of 1000 randomly generated distributions of galaxies containing the same number of points as in the actual fields.

It has been assumed that a substructure is real if the probability that the detected substructure is due to random fluctuations is less than 1%. Furthermore, for each scale a, only substructures with more than four galaxy members in a circle of radius a are considered. Moreover, following Escalera *et al.* (1994), we classified the structures morphologically according to two categories: unimodal and complex.

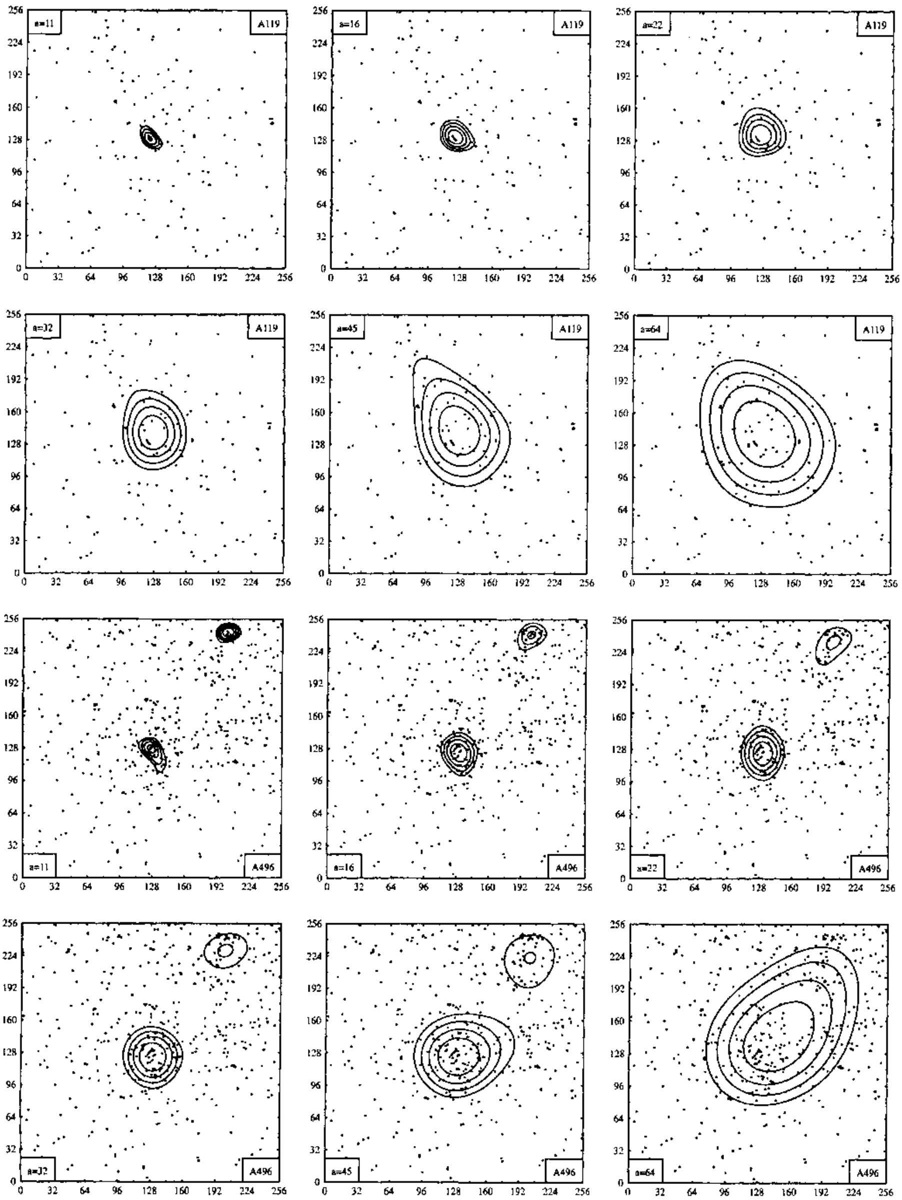

FIGURE 1 The distribution of galaxies in A119 and A496 with wavelet images for scales $a = 11$, 16, 22, 32, 45 and 64 pixels.

4 RESULTS

The results of the application of the wavelet analysis to the present galaxy cluster sample, together with the basic cluster parameter, are given in Table I. The first column contains the cluster name, and the second column the cluster type, after Abell *et al.* (1989), while the third and fourth columns list the right ascension and declination (1950) respectively. The fifth column presents the cluster red shift from Struble and Rood (1987),

TABLE I Properties of Investigated Clusters.

Cluster name	*Cluster type*	*Right ascension (1950) (h min)*	*Declination (1950) (deg arcmin)*	*Red shift z*	*Cooling flow*[a]	*Cluster morphology*[b]
A85	cD	00 39.1	−09 37	0.0518	CF	U
A119	C	00 53.8	−01 32	0.0440	NCF	U
A426	D	03 15.3	41 20	0.0183	CF	S
A496	cD	04 31.3	−13 21	0.0320	CF	S
A754	cD	09 06.4	−09 26	0.0528	NCF	S
A1367	F	11 41.9	20 07	0.0215	NCF	S
A1656	B	12 57.4	28 15	0.0222	NCF	S
A1750	cD	13 28.3	−01 35	0.0852	NCF	U
A1795	cD	13 46.7	26 50	0.0617	CF	U
A2029	cD	15 08.5	05 57	0.0767	CF	U
A2142	B	15 56.2	27 22	0.0899	CF	U
A2199	cD	16 26.9	39 38	0.0303	CF	S
A2256	B	17 06.6	78 47	0.0601	NCF	U
A2319	cD	19 19.2	43 52	0.0564	NCF	U
A3266	cD	04 30.5	−61 35	0.0594	NCF	U
A3376	L	05 59.1	−40 03	0.0455	NCF	S
A3562		13 30.7	−31 25	0.0483	CF	S

[a]CF, cooling flow; NCF, no cooling flow.
[b]U, unimodal; S, substructures present in the cluster.

while the sixth column shows the existence of the cooling flow or its absence. The seventh column gives the cluster morphology.

5 CONCLUSIONS

The method based on the wavelet transform has been applied to detect substructures in the projected distributions of galaxies in 17 hot rich Abell clusters. The significance of substructuring detected has been calibrated using simulated distributions by means of Monte Carlo modelling, performing 1000 simulations for each cluster and each scale. Upon applying the Mexican hat wavelet analysis to the projected distributions of galaxies in eight clusters with cooling flows, the subclustering was observed in four of them, which means that significant structures are present in 50% of cases. For non-cooling flow clusters, the frequency of substructures is $4/9 = 44\%$. A comparison with other investigations based both on the projected and three-dimensional data shows that, while in individual cases there are sometimes differences in finding substructures, the percentage of substructure occurrence is not greatly affected. Moreover, the finding of Kolokotronis *et al.* (2001) shows the correlation between cluster properties derived from the optical and X-ray spectra.

Therefore, even when the statistical difference between the two samples is negligible, owing to the smallness of the samples, the results show that at least there is some subclustering with cooling flow clusters. This is in good agreement with the result that, in general, cooling flow clusters have mainly regular shapes and unimodal X-ray surface brightness distribution, as well as the fact that ‘substructured cooling flow clusters are to be expected’ (Schuecker *et al.*, 2001).

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