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MORPHOLOGICAL CLASSIFICATION OF GALAXY CLUSTERS

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Abstract. We perform a quantitative morphological classification of a sample of low redshift galaxy clusters extracted from the SDSS C4 cluster catalogue. Clusters with a high spectroscopic coverage were selected. A wavelet based algorithm was applied allowing to detect and quantify 3D substructures and analyze the large scale environment of these clusters. Based on this classification, we study the correlation between cluster morphology and spectral properties of galaxy members.

Keywords: Galaxies: clusters: general, large scale structure of universe

1 Introduction

Galaxy clusters are the largest gravitationnally bound systems of the universe. According to the standard model of cosmology they have been formed recently through a hierarchical growth in which smaller units, the galaxies, assemble together. Numerous observations in X-rays (Jones & Forman 1999) as well as in optical (Geller & Beers 1982; Dressler & Shectman 1988) show that there are substructures in a non negligible fraction of clusters, revealing that clusters are currently in a non relaxed dynamical state. Not only substructures reveal clusters dynamical state but also they can lead to wrong estimation of cluster physical properties, such as their mass for instance. For this reason, the use of galaxy clusters as probe to evaluate the cosmological parameters must be done carefully. Thus quantifying cluster dynamical state is of prime importance to measure their mass correctly.

Several previous works were performed in order to establish cluster morphological classifications. First galaxy cluster classifications were done using cluster galaxy content. Bautz & Morgan (1970) developped a classification based on three classes of clusters plus two intermediate ones according that a cluster contains a cD (class I), the cluster BCG is intermediate between a cD and a Virgo-type giant elliptical (class II) and the cluster contains no dominant galaxy (class III). Also Rood & Sastry (1971) defined the famous "tuning fork" classification.

Due to projection effects optical cluster classifications were forsaken and X-rays observations were used to analyze cluster dynamical state through the gas. Furthermore the gas enables to have an idea about cluster stage of merging process that is observed while galaxies do not. Moreover X-rays give a continuous distribution (gas photons or temperature) while optical gives only points (position of galaxies) which made more difficult the statistical analysis of the galaxy distribution than the one of the gas. It is in this context that several powerfull statistical tools were developed to analyze cluster morphology in X-rays. Mohr et al. (1993) used the centroid shift to constrain the dynamical state of 5 clusters observed with the *Einstein Observatory.* This technique was also used on more clusters (Jones & Forman 1999; Schuecker et al. 2001). Buote & Tsai (1996) developed the power ratio method, consisting in measuring the ratio between statistical moments of cluster X-ray luminosity. Cluster ellipticity was also used to assess cluster relaxation (Kolokotronis et al. 2001; Melott et al. 2001; Plionis 2002).

Thanks to the development of multi-object spectroscopy numerous galaxy redshifts could have been measured and these redshifts enable to disentangle piled up structures along the line of sight, solving the problem of projection effects on galaxies. First analyses of galaxy redshifts were made in the beginning of the nineties. Several statistical tools were developed to evaluate cluster properties along the line of sight (e.g. Beers et al. 1990) and to check the gaussiannity of their redshift distribution (e.g. Ashman et al. 1994). Later new analyses

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of galaxy projected distribution were performed. The main idea of these is to transform galaxy positions into a continuous distribution function. Adaptive kernels have been used (Ramella et al. 2007) in this purpose like wavelet analysis (Ferrari et al. 2005; Flin & Krywult 2006).

The aim of the present analysis is to establish a new cluster classification based on galaxies. In this analysis, galaxy position and redshift are used to finely characterize cluster optical morphology. In future works, this classification will be used to study the impact of cluster morphology on cluster galaxy members and to try to constrain cosmological parameters using clusters more precisely by removing complexe systems or by assessing more accurate mass measurments.

In this paper, the assumption of a flat universe with $H_0 = 70\,\mathrm{km\,s^{-1}}$, $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$ is done.

2 Data description

Currently the Sloan Digital Sky Survey (Abazajian et al. 2004) is the best sky survey for the local universe. Miller et al. (2005) developped the C4 cluster finder algorithm and detected 749 clusters in SDSS DR2. C4 clusters are the baseline of the present analysis. Photometric and spectroscopic information of all galaxies falling within 5 Mpc from C4 cluster centers have been extracted into *C4 fields*. Only galaxies brighter than $r' = 17.77$ were selected as SDSS spectroscopy is complete up to this magnitude. As galaxy redshift will be used to analyze cluster morphology high spectroscopic completness is required (at least 60% was chosen) and numerous galaxies are needed (at least 50 was chosen). These two first criteria plus the removal of overlaps reduced the cluster sample from 749 to 179 fields. Sample clusters have redshifts ranging from 0.0294 to 0.1386, the median being 0.0834.

3 Morphological classification

Galaxy cluster morphology consists in measuring deviations from a relaxed cluster, typically by detecting substructures within clusters. The presence of substructures has been detected in X-rays and in optical but mainly in projection on the sky plane and in other studies along the line of sight with galaxy velocities only. The development of multi-object spectroscopy enables the measurement of numerous galaxy redshifts giving access to the information along the line of sight together with the galaxy positions. The aim of this analysis is to classify clusters into five categories: relaxed clusters, bimodal major mergers, minor mergers, multiple mergers and clusters in virialisation phase.

To do so, not only detecting substructures in the projected sky plane and along the line of sight is performed but also measuring deviations from a relaxed cluster other than substructures. Namely the detection of substructures along the line of sight is based on the assumption that an ideal relaxed cluster has a gaussian velocity distribution, thus detecting deviations from gaussiannity in the velocity distribution means that a cluster is not relaxed. In that purpose numerous statistical tests have been developped (see Beers et al. 1990, for instance). Here the assumption of gaussian velocity distribution is done and a gaussian mixture will be used to describe cluster galaxy velocities. Every cluster will be decomposed in gaussian peaks along the line of sight, some clusters will consist in one gaussian peak, others in two, three etc.... Clusters presenting one gaussian peak may be "relaxed". Indeed at this stage no information in projection on the sky plane has been used thus these clusters may correspond to bimodal clusters in projection on the sky plane and the guassian hypothesis may not be correct for these clusters. For single gaussian clusters their gaussiannity has to be evaluated. This is done by computing the χ^2 between the gaussian fit and the velocity distribution: bad χ^2 values ($\chi^2 \geq 0.2$) means that the velocity distribution does not follow a gaussian law.

The analysis of galaxy positions is more complexe than for redshifts. Actually for redshifts it is quite easy because their expected distribution is a gaussian law and several tools have been developped in that purpose. For galaxy positions, the expected distribution is the universal NFW profile (Navarro et al. 1995). However this distribution is much more complexe than a gaussian law and it is not possible, today, to describe a data set by a mixture of NFW profiles. In fact a continuous field is required to analyze galaxy positions instead of a discret data set. There are several ways to transform galaxy positions into their underlying distribution. Based on a multi-scale approach cluster density maps have been computed. The detailed desciption of the algorithm can be found in Ferrari et al. (2005). Briefly, it involves a wavelet decomposition of the galaxy positions performed on scales from which the significant structures are recombined to give the final map (following Eq. (C7) in Fadda et al. 1998). The scales correspond to the size of structures that will be reconstructed in the final image. Clusters and groups of galaxies have masses ranging between $10^{13}\,\mathrm{M}_\odot$ and $10^{15}\,\mathrm{M}_\odot$ and thus have sizes ranging between 0.3 Mpc and 2 Mpc. With a multi-scale approach, interesting scales can be selected and only these ones can be used to compute the final image, thus only structures with size between 0.3 Mpc and 2 Mpc will be considered. The computed image is a 10 Mpc square to detect cluster environment.

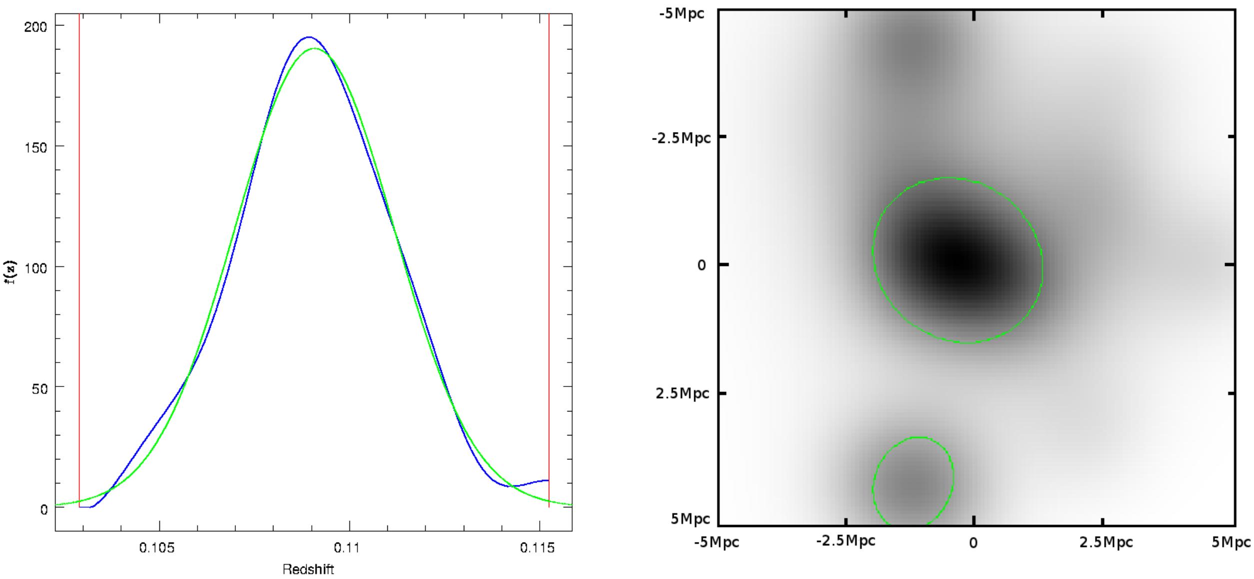

Fig. 1. Example of a relaxed cluster: cluster C4 0090. On the **left** panel its redshift distribution function (blue) reveals one gaussian peak (green) indicating no interaction along the line of sight. The red vertical lines indicates cluster redshift interval. On the **right** panel its density map reveals only two significant clumps (in green), but the distance between the clumps is too large with respect to their virial radius to indicate an interaction between them. Thus without interaction this cluster is classified as relaxed.

The right panel of Figure 1 shows the density map of C4 cluster 0090. On the right panel the density map reveals two significant clumps The central clump on density maps is the main cluster, the others may be other clusters, or groups pr substructures in the vicinity of the main cluster. The number of clumps is important for morphology but not all clumps are physically significant: only the ones close enough from the main cluster are interacting with it. The interaction depends on the distance between clumps but also on their mass. The criterion used for interaction is

$$d \leq r_{vir,1} + r_{vir,2}$$

where d is the physical distance between the main clump and the other clump and $r_{vir,i}$ is the virial radius of the clump. Furthermore the ellipticity of the cluster is an indication of its dynamical state. An ideal relaxed cluster has to be spherical and in projection has to appear circular. Large ellipticities ($\epsilon \geq 0.3$) indicate a non relaxed state of clusters. This parameter has to be taken into account for the morphology.

Finally clusters will be classified according to the following scheme:

- relaxed clusters: clusters presenting one gaussian peak ($\chi^2 \leq 0.2$) and one isolated clump ($\epsilon \leq 0.3$) in projection;
- bimodal major mergers: clusters presenting two massive components (with mass ratio greater than 1:2) (*i*) one gaussian peak (χ^2) and two massive interacting clumps, (*ii*) two close gaussian peaks and one clump in projection or (*iii*) two gaussian peaks corresponding to two massive clumps in projection;
- minor mergers: clusters having in their surrounding one or more structures with mass ratio between 1:2 and 1:5, they correspond to several gaussian peaks or several clumps in projection;
- multiple mergers: clusters having in their surroundings at least one other massive (with mass ratio greater than 1:2) cluster and one or several clumps less massive (with mass ratio between 1:2 and 1:5);
- clusters in virialisation phase or in merging state that do not allow to detect substructures: clusters with non gaussian peak or with a high ellipticity ($\epsilon \geq 0.3$).

4 Application to C4 clusters

The extraction method of galaxies in SDSS give fields of galaxies, *i.e.* a cone of galaxies, whose angular size corresponds to an angular size of 5 Mpc at the C4 cluster redshift. To disentangle piled up structures along the line of sight and keep only the cluster (namely to remove projection effects) galaxy redshift was used. The galaxy redshift distribution function (hereafter RDF) for each field has been computed using a multi-scale approach in the same way as for density maps but in one dimension. The redshift distribution function of the C4 cluster 0090 is represented in the left panel of Figure 1. By computing the RDF cluster redshift interval can be determined. Indeed the reconstruction algorithm removes the constant contribution of the signal and keeps only 3σ significant structures which means that the computed RDFs are composed by regions with significant signal delimited by regions with no signal. Clusters being galaxy concentration in the redshift space they contribute significantly to the RDF. In one field there may be several redshift regions with significant signal. The one containing the most galaxies appears to have the closest redshift to the corresponding C4 cluster thus this region will be the cluster redshift interval. In this interval of redshifts, galaxy redshifts will be analyzed to determine if they correspond to one or more gaussian peaks and if a single peak is found if this one is really gaussian or not. The decomposition of the RDF into a gaussian mixture is done by EMMIX software (McLachlan & Peel 1999). EMMIX detects all gaussian peaks nevertheless not all peaks are physically significant and only peaks more massive than $10^{13}\,\mathrm{M}_\odot$ are considered. EMMIX gives the three important parameters of the gaussian peaks: the mean, the standard deviation and the number of objects belonging to the peak. To assess the quality of the fit, χ^2 were computed between EMMIX gaussian fit and the RDF computed with the wavelet analysis. If the gaussian hypothesis is not correct for a cluter, its EMMIX fit will not be accurate and then its χ^2 will be high. The threshold value chosen to consider a cluster to be well fitted by a gaussian mixture is 0.2: higher values mean that cluster can not be described by a gaussian mixture.

Following the analysis along the line of sight, cluster density maps have been computed as described in section 3. The detection of clumps on density maps has been done using SExtractor software (Bertin & Arnouts 1996). SExtractor fits detections (clumps) in an image by ellipses and gives all their geometrical parameters (position, semi-major and minor axes, orientation . . .) and "physical" parameters (FWHM, flux in an isocontour . . .). Here the important parameters are the geometrical ones and the `FISO` parameter which is the flux in the lowest isocontour of clumps. Density maps being the projected galaxy distribution function, the `FISO` parameter measures the number of galaxies in the clumps. The cluster is the clump with the most galaxies thus the highest `FISO`. Only clumps that may be significantly interacting with the main cluster are kept, clumps with $\mathtt{FISO} \geq 0.1\mathtt{FISO}_{cluster}$. The interaction between clumps has to be verified as indicated in section 3. Virial radii are computed using Finn et al. (2008) formula (their Eq. 4). Galaxies are affected to their clumps and clump velocity dispersion is computed. Finally for isolated clusters (no cluster close and massive enough to interact) their ellipticity is compared to 0.3.

With cluster environment along the line of sight and in projection and the indication of gaussiannity and ellipticity, the 179 clusters were classified into the 5 categories. 59 clusters (33%) are relaxed, 10 (6%) are major bimodal mergers with mass ratio greater than 1:2. 56 clusters (31%) are minor mergers with mass ratio comprised between 1:2 and 1:5. 36 clusters (20%) are multiple mergers with at least one major merger and at least one minor merger. The last 18 clusters (10%) are in virialisation phase.

5 Conclusion

33% of relaxed clusters is in good agreement with previous studies which find between 30% and 70% of relaxed clusters in the local universe (Dressler & Shectman 1988). This classification gives a statistical sample of clusters to study environment effects on galaxies according to their cluster dynamical state and see if (*i*) there is a correlation between the cluster morphology and the fraction of star forming galaxies and if (*ii*) the cluster morphology has an impact on the distribution of star forming galaxies: if they are distributed rather in cluster outskirts or innerparts.

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