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GALAXY CLUSTERS IN THE COSMIC WEB

A. Acebrón[2,1], F. Durret[2], N. Martinet[2], C. Adami[3], L. Guennou[4] and the DAFT/FADA team

Abstract. Simulations of large scale structure formation in the universe predict that matter is essentially distributed along filaments at the intersection of which lie galaxy clusters. We have analysed 9 clusters in the redshift range $0.4 < z < 0.9$ from the DAFT/FADA survey, which combines deep large field multi-band imaging and spectroscopic data, in order to detect filaments and/or structures around these clusters. Based on colour-magnitude diagrams, we have selected the galaxies likely to be in the cluster redshift range and studied their spatial distribution. We detect a number of structures and filaments around several clusters, proving that colour-magnitude diagrams are a reliable method to detect filaments around galaxy clusters. Since this method excludes blue (spiral) galaxies at the cluster redshift, we also apply the LePhare software to compute photometric redshifts from BVRIZ images to select galaxy cluster members and study their spatial distribution. We then find that, if only galaxies classified as early-type by LePhare are considered, we obtain the same distribution than with a red sequence selection, while taking into account late-type galaxies just pollutes the background level and deteriorates our detections. The photometric redshift based method therefore does not provide any additional information.

Keywords: Cosmology, Cosmic Web, Filaments, Galaxy Clusters

1 Introduction

Formation and evolution of structures in the Universe is still one of the major issues in modern astronomy. N-body simulations of the dark matter distribution on very large scales (Bond et al. 1996) predict that structures of galaxies consist of rich and poor clusters, connected by filaments and sheets, with regions largely devoid of galaxies (voids) in between. Due to the recent availability of new, better quality, wide and deep field surveys, intensive observations followed (large galaxy redshift surveys, York et al. 2010 for instance) showing that matter is not randomly distributed but is rather concentrated along filaments at the intersection of which lie galaxy clusters forming the cosmic web. However, fewer investigations have focussed on the detection of filaments around galaxy clusters in order to comprehend their formation and evolution processes.
In hierarchical structure formation modelling, galaxy clusters grow through repeated mergers with other galaxy clusters, groups, etc., but also accreting matter from their environment (Zeldovich et al. 1982) which occurs in a highly non-isotropic manner: galaxy filaments feed clusters along preferred directions (Pimbblet, 2005).
Although ubiquitous in large-scale galaxy surveys, filaments have proven difficult to characterise physically, owing to their low density or because elongated structures of galaxies in some cases turn out to be the result of recent cluster mergers. Colour-magnitude diagrams and photometric redshift computations are the most efficient methods to analyse wide fields.
Previous works have shown that the detection of filaments around galaxy clusters is possible though (see for example: Dietrich et al. 2005 and 2012; Tanaka et al. 2007; Jauzac et al. 2012). The DAFT/FADA (Dark energy American French Team, PIs: C. Adami, M. Ulmer, and D. Clowe) program, which is a combined France/USA effort, aims to produce a large survey of rich clusters with photometric redshifts for all the galaxies, by combining HST archives with ground-based photometry on 4m class telescopes, of 90 high redshift ($0.4 < z < 0.9$) massive

[1] Observatoire de Paris-Meudon, UFE, 92195 Meudon Cedex, France
[2] UPMC Université Paris 06, UMR 7095, Institut d'Astrophysique de Paris, 98bis Bd Arago, F-75014, Paris, France
[3] LAM, OAMP, Université Aix-Marseille & CNRS, Pôle de l'Etoile, Site de Château Gombert, 38 rue Frédéric Joliot-Curie, 13388 Marseille 13 Cedex, France
[4] IAS, CNRS & Université Paris Sud, Bâtiment 121, 91405 Orsay, France

(M > 2 × 10^{14} $M_\odot$) clusters of galaxies. DAFT/FADA is therefore a promising database to detect filaments around galaxy clusters.
We have focused on the analysis of coulour-magnitude diagrams and photometric redshift computations from BVRIz bands with the aim of detecting large scale structures around several clusters.
We present hereafter in section 2 the data and methods used in this study, followed in section 3, by the results and discussion. Throughout the report, we use the standard cosmological model with $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$ and $H_0 = 70$ km s^{-1} Mpc^{-1}.

2 Data and methods

2.1 The optical and spectroscopic data

In order to detect filaments and/or groups of galaxies around galaxy clusters we use deep wide-field multi-band imaging (see details on the reduction process in Guennou et al. 2010) and spectroscopic data.
From all the clusters of the DAFT/FADA database we only consider clusters having good-quality deep wide field images (since we aim to detect large-scale structures) and spectroscopic redshift catalogues, retrieved from the NED archive, in a 30 arcmin radius around each cluster. The coordinates of the cluster centers are taken from NASA/IPAC Extragalactic Database (NED, `http://ned.ipac.caltech.edu/`).
Our data come in majority from 4m to 8m class telescopes like the Canada France Hawaii Telescope (CFHT, 3.6m), Subaru (8.2m), SOAR (4.1m). The images were obtained using the dithering technique.
For each cluster we work with 5 different bands (B or u, V or g, R, I, z). We use only V or g and I for the colour-magnitude diagrams and all the bands to compute photometric redshits with LePhare package in section 3. We have analyzed 9 clusters in the redshift range 0.4<z<0.9.

2.2 Coulour-magnitude diagrams

In this section we present all the steps to obtain colour-magnitude diagrams in order to select early-type galaxies at redshifts close to that of the cluster. We plot V-I as a function of I in order to encompass the Balmer break (400 nm) in this redshift range.
SExtractor (Bertin & Arnouts 1996) is used to extract the magnitudes (in the AB system) of all the sources in our images in the V and I bands separately. SExtractor extracts not only galaxies and stars but also defects in the image.
Since we are only interested in analyzing galaxy magnitudes, we separate stars and defects from galaxies in our I band catalogue. To do so, we plot the maximum surface brightness $\mu_{max}(I)$ in the I band as a function of I. Stars and defects are located in precise regions in this plot and can easily be removed from our catalogues.
We only consider galaxies with a magnitude brighter than I=23, which is the completeness level for the clusters we have studied. Thus, we obtain a catalogue containing only galaxies brighter than I=23, for which we also measured magnitudes in the V band and added spectroscopic redshifts when available.
Magnitudes are corrected for Galactic dust extinction using the Galactic dust full-sky maps of Schlegel et al. (1998).

The (V-I) vs. I colour-magnitude diagram is shown in Fig. 1 for the cluster MACS 0717.5+3745. Since we are working on large field images, we detect many sources that, at first sight, pollute the red sequence. We then plot the galaxies located in a radius of 1 Mpc from the cluster centre in order to better detect the cluster red sequence. Also, the galaxies having spectroscopic data, allow us to clearly identify the red sequence since they are located on it. We compute the best fit to the (V-I) vs. I relations for magnitudes I≤23 by applying a linear regression to the galaxies located in a radius of 1 Mpc around the central coordinates (taken from NED). We then eliminate the galaxies located more than ±0.6 away from this relation and recompute the (V-I) vs. I relation, keeping the galaxies located ±0.3 mag away from the sequence as shown in Fig. 1. These galaxies thus have a high probability of being at the same redshift as the cluster.
With this method we select galaxies with a high probability to belong to the cluster but, in the process, we lose some spiral (blue) galaxies which can be at the cluster redshift but fall below the red sequence.

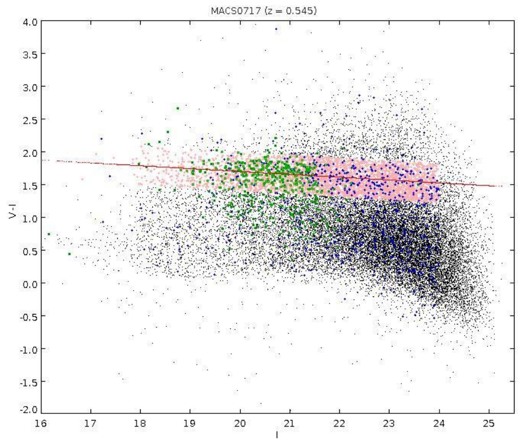

Fig. 1. (V - I) vs I colour-magnitude diagram for MACS 0717.5+3745. The black points show all the galaxies in the images. The blue points correspond to the galaxies located in a radius of 1 Mpc from the cluster centre. The green points are the galaxies with spectroscopic redshifts in the cluster. The pink points are the galaxies located ±0.3 mag away from the cluster red sequence, and are considered to be at the cluster redshift (see text).

2.3 Photometric redshift computation

We now present a second method to detect filaments around the clusters in our sample. The first DAFT/FADA paper (Guennou et al. 2010) established the reference basis for the photometric redshift computation.
Having a large sample of spectroscopic redshifts is obviously a better and a more precise way to detect filaments than using photometric redshifts. However, obtaining a large sample of spectroscopic redshifts requires a great amount of telescope time, while photometric redshifts can be computed for very large samples of galaxies, but of course with a lower precision than spectroscopic redshifts. We compute our photometric redshifts (hereafter photo-zs) with the LePhare package (see Arnouts et al. 1999; Ilbert et al. 2006 for details) and present here the main points of the technique.
We provide LePhare with a catalogue including, for each object, the coordinates of the object, the magnitudes (extinction corrected) in all 5 optical bands and their errors, and spectroscopic redshifts when available. LePhare compares the observed magnitudes with those of template galaxies with the aim of estimating the redshift and/or other parameters, such as the photometric type (numbers 1-7 correspond to early type galaxies, numbers 8-12 to early spirals galaxies, numbers 20-31 to very blue galaxies).
The program performs a χ^2 fitting analysis between the observed and template fluxes to estimate the redshift. Since we did not observe all the clusters with the same telescope and filters (and even for some clusters, the data in the 5 bands came from various telescopes), we had to convert our magnitudes into a single magnitude system (the VLT/FORS2 BVRIz system) with LePhare. This was done in particuler to compare our photo-zs based on 5 optical bands with those of Martinet et al. (2014), who used one more band (infrared), and therefore obtained photo-zs expected to be more precise, but in smaller fields (the infrared images are smaller than the optical ones).
We also included spectroscopic redshifts as inputs (when available) since LePhare can estimate possible shifts in photometric zero-points by comparing the photometric and spectroscopic redshifts.
The comparison of the 5 band and 6 band photo-zs shows they are in quite good agreement in the redshift range $0.45 < z < 0.9$, so we will be able to search for large scale structures based on the photo-zs we obtained in the large fields covered by the 5 optical bands.

3 Results

We show in Fig. 2 the distribution maps of the galaxies selected by colour-magnitude relations for three clusters: MACS 1621.4+3810, MACS 1423.8+2404 and MACS 0717.5+3745. The galaxy distributions around these clusters show clear elongations of several Mpc in length.
The six other clusters that we analysed do not show clear elongations.

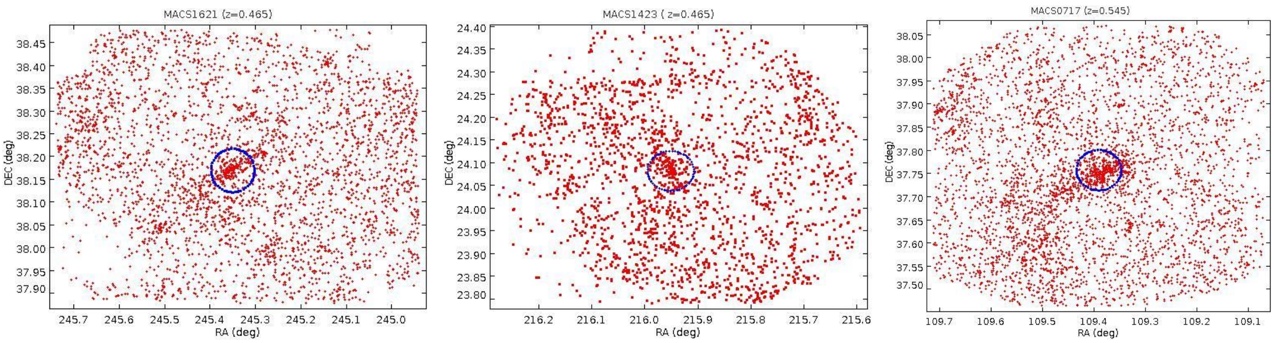

Fig. 2. Distribution maps of the galaxies selected to be at redshifts similar to those of the clusters, based on the (V-I) vs. I colour-magnitude diagrams, for MACS 1621.4+3810 (left), MACS 1423.8+2404 (center) and MACS 0717.5+3745 (right). The blue circles show the positions of the cluster centers according to the NED/IPAC coordinates and have a radius of 1 Mpc.

4 Discussion and conclusions

The DAFT/FADA project possesses a promising database to analyse large scale structures such as filaments and/or groups around galaxy clusters. We have searched for filaments around 9 galaxy clusters with two different methods based on optical imaging and spectroscopic data.
The colour-magnitude diagram method has proven to be reliable for this cosmic quest: we have detected elongations of several Mpc around several clusters.
We have also tested computing photo-zs using 5 optical bands and compared our results with 6-band photo-zs. The selection based on photometric redshifts hasn't given any additional information relatively to that based on the colour-magnitude relation, since only elliptical galaxies are well constrained by LePhare.
Although the methods we have used have some limitations (only ellipticals are considered with colour-magnitude diagrams and late-type galaxies are badly constrained with LePhare), they nonetheless do allow to reliably detect elongations. For example, the elongation found in MACS 0717.5+3745 is confirmed by weak lensing and spectroscopy (Jauzac et al. 2012, Martinet et al. 2015, in preparation).
Another limitation of our work is that galaxy filaments do not have yet a specific definition (Pimbblet, 2005): do they have to have a minumum length, are they above a threshold in the galaxy density relative to the average background level, etc? This lack of precise definition will certainly require further analysis.
As a continuation of the work presented here, we intend to apply the colour-magnitude diagram method to the 18 remaining DAFT/FADA clusters for which we have deep wide field imaging), and also to other surveys like the CFHTLS which has more than 4000 candidate clusters up to z=1.4 detected by our team (Durret et al. 2011).

Once a great number of filaments has been detected around clusters, the properties of galaxies in the filaments could also be analyzed, such as the morphological properties of the galaxies in the filaments (early-type, late-type) and also the position angles of their spins relative to the filament.

Continuing this cosmic quest and detecting filaments around galaxy clusters would thus help us to understand better the formation and evolution of galaxy clusters.

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