Testing for substructure in optical and X–ray clusters

V. Kolokotronis\textsuperscript{1}, S. Basilakos\textsuperscript{1,2,3}, M. Plionis\textsuperscript{1}, I. Georgantopoulos\textsuperscript{1},

\textsuperscript{1}Astronomical Institute, National Observatory of Athens, I Metaxa & B. Pavlou, Palaia Penteli, 15236, Athens, Greece
\textsuperscript{2}Physics Department University of Athens, Panepistimiopolis, Zografos, Athens, Greece
\textsuperscript{3}Imperial College of Science, Technology and Medicine, Blackett Laboratory, Prince Consort Road, London SW1 2EZ, UK

Abstract. We present a detailed study of the morphological features of 22 rich galaxy clusters. We systematically compare cluster images and morphological parameters in an attempt to reliably identify possible substructure in both optical and X–ray images. To this end, we compute moments of the surface-brightness distribution to estimate ellipticities, center-of-mass shifts and orientations. We find important correlations between the optical and X–ray morphological shape parameters. Most of our clusters (17) have a good 1-to-1 correspondence between the optical and the X–ray images and at least 9 appear to have strong indications of substructure. This corresponds to a percentage of $\sim 40\%$ in good accordance with other similar analyses. Finally, 4 out of 22 systems seem to have distinct subclumps in the optical which are not verified in the X–ray images, and thus are suspect of being due to optical projection effects. We assess the significance of results using Monte Carlo simulations.

1 Introduction

One of the most significant properties of galaxy clusters is the relation between their dynamical state and the underlying cosmology. In an open universe, clustering effectively freezes at high redshifts and clusters today should appear more relaxed with weak or no indications of substructure. Instead, in a critical density model, such systems continue to form even today and are expected to be dynamically active. The percentage and morphologies of disordered objects in a cluster sample could lead to crucial constraints on $\Omega_c$ and $\Lambda$, especially if combined with N-body/gas-dynamic numerical simulations spanning different dark matter (DM) scenarios ([1]; [3]; [2]).

A large number of relevant analyses have been devoted to this study and an accordingly varying and large number of optical and X–ray cluster compilations have been utilised to this aim ([1]; [3]; [2] and references therein). In the present work, we use a sample of 22 galaxy clusters (APM and ROSAT) in a complementary fashion with the aim to address the following two questions:

- Is substructure in the X–ray also corroborated by the optical observations and in what percentage?
What is the percentage of systems depicting strong indications of subclumping and what does it imply for the existing cosmology?

2 Data & Methodology

The present dataset follows from a double cross-correlation between rich ACO clusters (R ≥ 1,2,3) with the APM cluster catalogue and the X-ray (0.1 - 2.4) keV ROSAT pointed observations archive, finally resulting in 27 common entries. Due to problematic regions of the APM catalogue, low signal to noise X-ray observations and contamination by known foreground or background objects, we exclude 5 clusters reducing our cluster sample to 22 systems. The redshift range of our sample is 0.04 ≤ z ≤ 0.13 with ⟨z⟩ ~ 0.074 and median ~ 0.069. For the needs of our analysis we transform cluster redshifts to distances using the luminosity-distance relation for a critical density model, q0 = 0.5 and H0 = 100 h km s⁻¹ Mpc⁻¹.

In order to construct a common comparison base, we create a continuous density field for both optical and X-ray data by using a Gaussian Kernel and a variable smoothing length according to each cluster redshift. However, so as to take into account the reduction of the number of cluster members as a function of distance (due to the APM magnitude limit), and thus the corresponding increase of discreteness effects, we have investigated, using Monte-Carlo cluster simulations, the necessary size of the smoothing window in order to minimise such effects and optimize the performance of our procedure (cf. [7]). We then compute the optical and X-ray cluster shape parameters utilising the method of moments of inertia. The eigenvalues and the eigenvectors of the inertia tensor can provide us with the cluster ellipticities and major axis orientations (position angles) respectively. We also define the centroid shift as the vectorial difference between the weighted cluster center-of-mass and the highest cluster density peak (cf. [3], [4]). These shape parameters are estimated using all cells that have densities above three thresholds. These are defined as the average density of all cells that fall within a chosen radius. The three radii used are r₁ = 0.3, 0.45 and 0.6 h⁻¹ Mpc, whereas the maximum searching radius for all subsequent calculations is 0.8h⁻¹ Mpc. We finally utilise a friend-of-friends algorithm to investigate possible substructure by joining all cells having common boundaries and fall above each density threshold. We therefore create and register all subgroups as a function of density threshold and rank substructure according to different criteria (cf. [8]).

3 Quantifying substructure results

Looking at the cluster shape parameters and visually inspecting the isodensity contour maps (see Figure 1 for a subsample of 4 objects), we do observe a remarkable 1-to-1 correspondence in ≤ 80% of our sample regarding the gross structural
Figure 1: Optical and X-ray images of galaxy clusters. Contours correspond to the X-ray data, whereas greyscale configurations denote the optical.

features (prime and secondary components, elongations, irregular activity, collision vestiges, unimodality). The majority of the optical and X-ray images are very well aligned with $\langle \delta \theta \rangle \leq 20^\circ$ and relative correlation coefficient of order of $\geq 0.9$, which is also highly significant. Furthermore, the ellipticities and the centroid shifts between optical and X-ray data do correlate well with coefficient of order $\sim 0.7$ in both cases. On the other hand, we have found important intrinsic correlations between ellipticities and centroid variations in the optical and the X-ray configurations separately, with relative coefficients ranging from 0.6 to 0.8 respectively. Cross-correlating the optical and X-ray substructure measures, we discover that they also correlate nicely. Probably the most interesting correlation is that between optical centroid shifts and X-ray ellipticities, with a value exceeding 0.8. This indicates that we can deduce the shape of the DM gravitational
potential from optical cluster data.

Since random density fluctuations as well as background contamination may introduce spurious substructure, we quantify the significance of our substructure measures, as revealed by the center of mass shift in the optical, using Monte Carlo cluster simulations with the same number of galaxies, ellipticity and estimated background as that of each cluster in our sample. This significance is estimated by measuring the deviation of the true cluster center-of-mass shift, from the corresponding simulated value in units of the estimated \( \sigma \) from 100 Monte-Carlo simulations of each cluster. We also compare this significance measure to the results of the subgroup statistics algorithm. The two measures are significantly correlated with a value of \( > 0.7 \).

Finally we classify our clusters according to their morphological parameters using a scheme which is very close to the one developed by [6]. Results indicate that our findings are in very good agreement with those of [6] both on a quantitative and qualitative basis. Note also, that 11 out of our 22 clusters have been examined for substructure signals elsewhere in the literature. We have checked that our computations on the cluster shape parameters do accord with those of the other studies. (\[1\]; \[3\]; \[6\])

From our prime substructure analysis we confirm that at least 9 out of 22 systems display strong substructure indications visible in both parts of the spectrum. We also find that 4 clusters (\( \leq 20\% \)) show clear disparities between the optical and X-ray maps, with apparent substructure in the optical not corroborated by the X-ray data. The rest of our sample exhibits no or insignificant substructure indications. We finally observe that our present study is compatible with that of \[1\] (their Figure 2) regarding the cluster substructure frequency, setting a rather frail lower limit on the density parameter (\( \Omega_0 \geq 0.5 \)).

In the near future we plan to apply the methodology of this work to the large optical APM sample of galaxy clusters (> 900 entries), in order to investigate in more detail the issue of cluster substructure.

Acknowledgements. V. Kolokotronis and S. Basilakos wish to acknowledge financial support from the Greek State Fellowship Foundation.

References

[1] Richstone D., Loeb A., Turner E. L., 1992, ApJ, 393, 477  
[2] Thomas P. A. et al., 1998, MNRAS, 296, 1061  
[3] Evrard A. E., Mohr J. J., Fabricant D. G., Geller M. J., 1993, ApJ, 419, L9  
[4] Mohr J. J., Evrard A. E., Fabricant D. G., Geller M. J., 1995, ApJ, 447, 8  
[5] Buote D., Tsai J., 1996, MNRAS, 458, 27  
[6] Jones C., Forman W., 1999, ApJ, 511, 65  
[7] Basilakos S., Plionis M., Maddox S. J., 1999, MNRAS, \textit{submitted}