New method of the investigation of alignment of galaxies in clusters

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Various models of galaxy formation can account for various aspects of the galaxy and structures formation process on different scales. The different scenarios predict different type of galaxy alignment which enables for observational test of various models. This gives us the method for testing scenarios of galaxy formation. In the paper we compare the theoretical prediction with observation results and with results obtained from simulation. We will finish the paper by discussing the implications of the results for the theories of galaxy formation.

1 Introduction

In our previous papers (Stephanovich & Godłowski, 2015, 2017) it has been shown that the angular momentum of galaxy clusters should be increasing with mass of the structures and increasing during time i.e. decreasing with redshift. In the present paper we will compare the results of the theoretical analysis of the relation between angular momentum and mass (richness) of the galaxy clusters with the results obtained by large scale structure simulations (based on the illustris project) and with the results obtained from the analysis of the real sample of galaxy clusters. Because during analysis of the observational data the angular momenta of galaxies are usually not known, we analyzed alignment of member galaxies (for details see Pajowska et al. 2019) instead. We use the extended method of analysis of the alignment of galaxies in clusters discussed in Pajowska et al. (2019). Our results have shown more explicitly that the alignment in galaxy clusters truly exists and moreover it increases with age and mass of the clusters.

2 Data

The sample of 6188 PF Catalogue clusters is our observational basis. Catalogues have been obtained from Muenster Red Sky Survey (Ungruhe et al., 2003) using Voronoi tessellation technique (Ramella et al., 1999, 2001). The PF Catalogue is statistically complete for objects brighter than 18.3^m. Usually the distance to the structures in PF Catalogue have been determined using the tenth brightest galaxy dependence form: $\log(z_{\rm est}) = -3.771 + 0.166\, m_{10}$ (Panko et al., 2009) eliminating the error associated with peculiar motion of galaxies. However in the present paper we decided to restrict to subsample of 187 rich clusters (with at least 100 members galaxies) which have Abell identification and also directly obtained spectroscopic redshift. Because a sample of 187 is not very rich we enlarged it for sample of 377 rich Abell cluster selected from the base of DSS. They are clusters from ACO Catalogue (Abell et al., 1989) with galactic latitude $b > 40°$, richness class ≥ 1 and

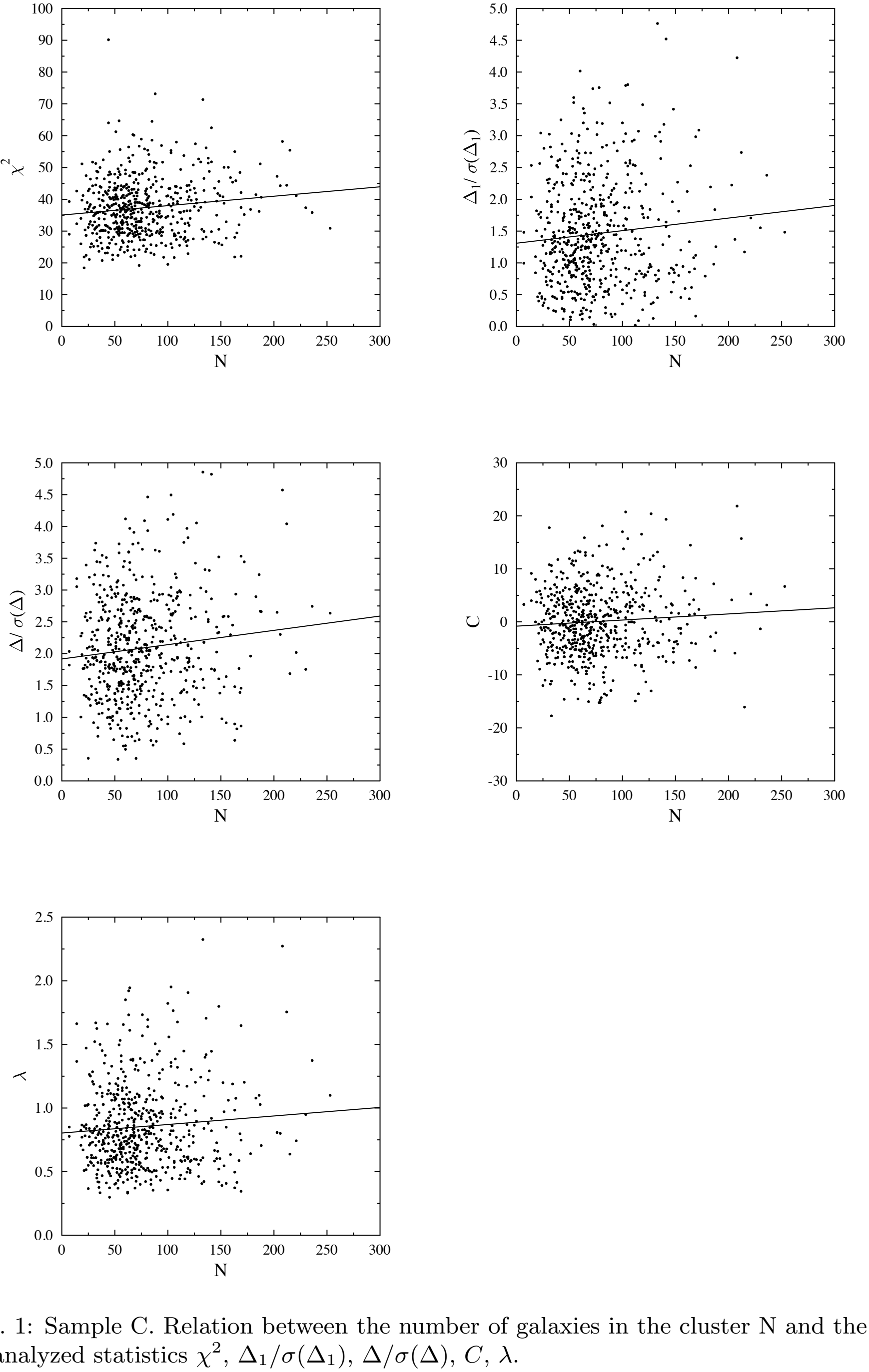

Fig. 1: Sample C. Relation between the number of galaxies in the cluster N and the value of analyzed statistics χ^2, $\Delta_1/\sigma(\Delta_1)$, $\Delta/\sigma(\Delta)$, C, λ.

redshifts $z < 0.2$ (Struble & Rood, 1999). So, our full sample of galaxies contains 564 clusters.

Independently, we used the simulation data coming from Illustris Project which

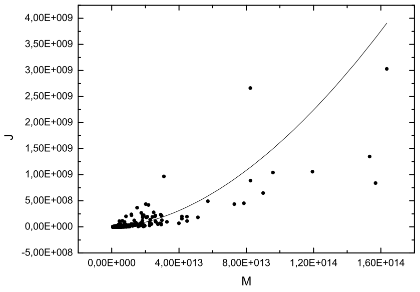

Fig. 2: Illustris simulation. Relation between Angular Momentum and Mass of the Cluster. Mass > 10^{12} Solar Mass.

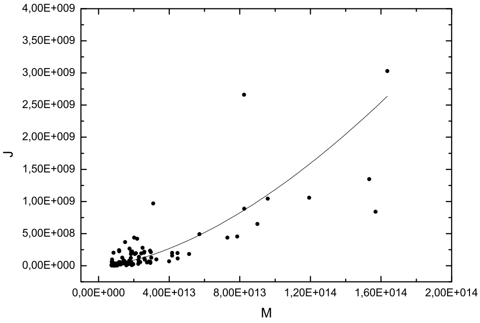

Fig. 3: Illustris simulation. Relation between Angular Momentum and Mass of the Cluster. Mass > 10^{13} Solar Mass.

uses the AREPO code for hydrodynamic realization of a 106.5 Mpc^3 cosmological volume for multiple resolution runs (Springel 2010) with ΛCDM cosmology. The highest resolution was performed for Illustris-1 from which we selected Halos at redshift $z = 0$ identified with SUBFIND algorithm (Davis et al., 1985; Springel et al., 2001; Dolag et al., 2009). 119 Halos with total mass greater than 10^{13} $M_\odot$ and 1435 with mass greater than 10^{12} $M_\odot$ were obtained. The angular momentum was the parameter added from the catalogue from Zjupa & Springel (2017).

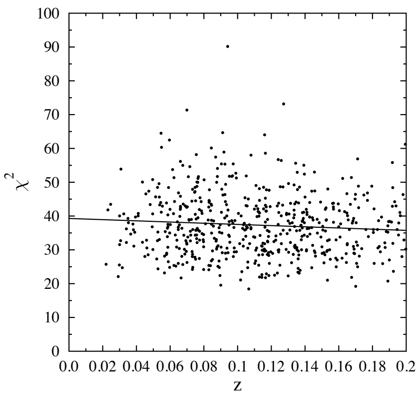

Fig. 4: Sample C. Relation between the redshift z and the value of analyzed statistics χ^2.

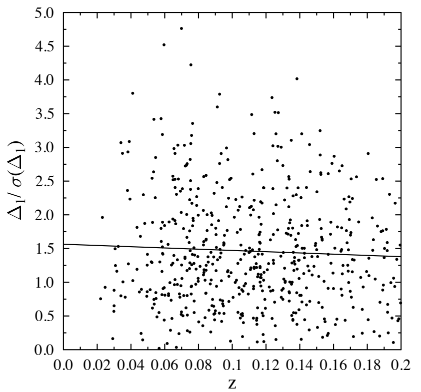

Fig. 5: Sample C. Relation between the redshift z and the value of analyzed statistics $\Delta_1/\sigma(\Delta_1)$.

3 Results and conclusions

(Hawley & Peebles, 1975) gives a proposal of the analysis of the distribution of galaxies angular momentum by the distribution of the observed position angle of the galactic image major axis. The idea is to use the statistical tests for the investigation of the galaxies orientation in the large structures, while the greater value of statistic means greater alignment of galaxies angular momentum. Since then, this method has become the standard method of searching for galactic alignments. Last

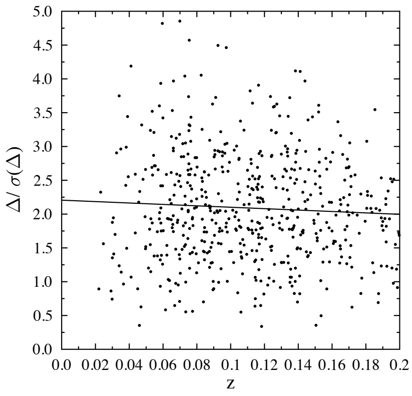

Fig. 6: Sample C. Relation between the redshift z and the value of analyzed statistics $\Delta/\sigma(\Delta)$.

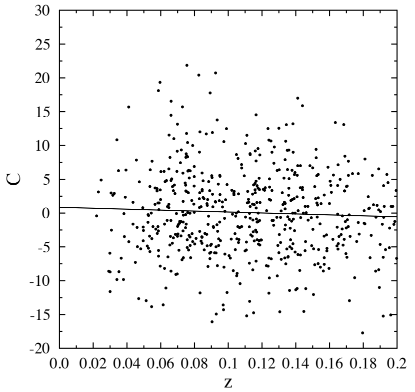

Fig. 7: Sample C. Relation between the redshift z and the value of analyzed statistics C.

Tab. 1: Relation between Angular Momentum and Mass of the Cluster from the Illustris simulation.

Mass	a	σa	$t = a/\sigma a$
$> 10^{12}$	1.807	0.028	66.93
$> 10^{13}$	1.708	0.114	14.94

improvement and revision of this method was presented in Pajowska et al. (2019). By using this method it is possible both to analyze dependence on alignment on particular parameter like richness of galaxy cluster (Godłowski et al., 2010) and to quantitatively answer the question if the alignment is present in the sample (see Pajowska et al. 2019 for last revision). In our previous papers (Godłowski et al., 2010; Stephanovich & Godłowski, 2017), using sample of 247 PF rich Abell clusters it has been shown that the alignment of galaxies in clusters significantly increases with cluster richness, while data was insufficient to give conclusion about dependence of analyzed statistic from redshift z.

We performed the investigation of the linear regression given by $Y = aX + b$ counted for various parameters. The Y are the values of analyzed statistics i.e. χ^2, $\Delta_1/\sigma(\Delta_1)$, $\Delta/\sigma(\Delta)$, C and λ (χ^2 is the statistics of χ^2 test, Δ_1 and Δ are the amplitudes of the Fourier test, C is the statistics of the first auto-correlation test, λ is the statistics of the Kolmogorov- Smirnov test) (see Stephanovich & Godłowski (2017) for details) while X is the number of analyzed galaxies in each particular cluster or cluster redshift z respectively. Our null hypothesis H_0 is that analyzed statistics Y does not depend on X. In such a case the statistics $t = a/\sigma(a)$ has Student's distribution with $u - 2$ degrees of freedom, where u is the number of analyzed clusters. It means that we have tested H_0 hypothesis that $t = 0$ against H_1 hypothesis that $t > 0$. In order to reject the H_0 hypothesis, the value of the observed statistics t should be greater than $t_{\rm cr}$ which could be obtained from the statistical tables. For example for sample 247 analyzed in Stephanovich & Godłowski (2017) at the significance level $\alpha = 0.05$, the value $t_{\rm cr} = 1.651$. The results are presented in

Tab. 2: The statistics $t = a/\sigma(a)$ for our sample of Abell clusters. Sample A - 187 rich Abell clusters from PF catalogue, Sample B - 377 DSS rich Abell clusters, Sample C - full sample 564 clusters (directly know redshift). ($f(N)$ - is the function depending on the number of galaxies, $f(z)$ - is the function depending on redshift).

Test	$S = f(N)$ Sample A	$S = f(z)$	$S = f(N)$ Sample B	$S = f(z)$	$S = f(N)$ Sample C	$S = f(z)$
χ^2	2.041	−1.889	3.241	−1.857	3.402	−2.342
$\Delta_1/\sigma(\Delta_1)$	1.583	0.494	0.600	−0.864	2.857	−1.452
$\Delta/\sigma(\Delta)$	1.917	−0.208	1.200	−0.86	3.142	−1.646
C	1.733	0.474	0.108	−1.353	1.825	−1.305
λ	2.000	0.644	2.250	−2.069	2.333	−1.953

the Tab. 2, 3. Table 2 shows that from analysis full sample of 564 clusters we could conclude that analyzed statistics i.e. the alignment significantly increases with the richness of the cluster. This confirms the result obtained in Godłowski et al. (2010); Stephanovich & Godłowski (2017) as well as the theoretical prediction (Stephanovich & Godłowski, 2015). Details are also presented in Fig. 1.

Moreover, the alignment decreases with z, what means that it increases with time as predicted by (Stephanovich & Godłowski, 2015, 2017). However, one should note that, mostly because of the observational bias, the richness of our cluster is also decreasing with redshift z. In linear model $N(z) = az + b$ the value of $t = -7.066$. It is the reason why we repeated our analysis as 3D model $Y = S_1 * N + S_2 * z + c$ Now the test statistic t is given by formula $t_1 = S_1/\sigma(S_1)$ and $t_2 = S_2/\sigma(S_2)$. From Tab. 3 we can confirm that alignment increases with the richness (Fig. 1) of the cluster and decreasing with z (Fig. 4, 5, 6, 7), however, the effect is smaller than suggested by the 2D analysis only and in the case of redshift to week to be statysticaly confirmed at the significance level $\alpha = 0.05$.

Analysis of Illustris simulation (Tab. 1) confirms that angular momentum of the cluster is increasing with the redshift. Moreover because these simulations give direct values both of mass of the structures and of the angular momentum of the structures it is possible to analyze possible shape of dependence in more detail. The model is power law $J = b * M^a$, (where M stands for mass) which easily could be recomputed to the linear model $\ln J = \ln b + a \ln M$. The result of the analysis shows that the value of coefficient $a = 1.807 + / - 0.028$ (Fig. 2). When analyze the sample of only the most massive cluster (mass $M > 10^{13}$ solar mass) $a = 1.708 + / - 0.114$ (Fig. 3) which is near to most popular theoretical prediction i.e. $a = 5/3$ (see Stephanovich & Godłowski (2015, 2017) for details). Finally one should note that our results agree with commonly preferred model of the galaxies formation i.e. so-called hierarchic clustering model Peebles (1969) recently improved by taking into account tidal torque scenario.

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Tab. 3: The statistics $t = a/\sigma(a)$ for 3D analysis our sample of Abell clusters. Sample A - 187 rich Abell clusters from PF catalogue, Sample B - 377 DSS rich Abell clusters, Sample C - full sample 564 clusters (directly know redshift).

Test	$S = f(N)$	$S = f(z)$	$S = f(N)$	$S = f(z)$	$S = f(N)$	$S = f(z)$
	Sample A		Sample B		Sample C	
χ^2	1.790	-1.603	2.803	-0.945	2.846	-1.434
$\Delta_1/\sigma(\Delta_1)$	1.538	0.726	0.300	-0.728	2.250	-0.718
$\Delta/\sigma(\Delta)$	1.769	0.070	1.000	-0.566	2.625	-0.811
C	1.830	0.739	-2.999	-1.383	1.538	-0.814
λ	2.200	0.986	-0.500	-2.109	2.000	-1.302

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