New method of investigation of the alignment of galaxies

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The aim of modern extragalactic astronomy and cosmology which play an important part is the problem of structures formation. Investigating the orientation of galaxies is a standard test for scenarios of galaxy formation since different theories of galaxy formation make various predictions regarding to the angular momentum of galaxies. A new method of analysing the galaxies alignment in clusters was proposed by Godłowski (2012). Now this method was improved and not only the distribution of position angles for galaxy major axes was analysed, but in addition the distribution of the two angles describing the spatial orientation of the galaxy plane. We analysed the orientation of galaxies in 247 Abell rich galaxy clusters taken from Panko & Flin (2006) catalogue of galaxy clusters. We found that the orientations of galaxies in analysed clusters are not random. It means that we confirmed an existence of the alignment of galaxies in rich Abells' galaxy clusters genuinely. The implications of this results were discussed with reference to theories of galaxy formation as well.

1 Introduction

Different theories of galaxy formation make various predictions regarding to the angular momentum of galaxies. The most important class of models for structure formations are primordial turbulences, hierarchical clustering or Zeldovich's pancakes. These classical scenarios are still valid in the sense that novel models, considered in the present project are their improved modifications (see for example (see for example Lee & Pen, 2001a,b, 2002; Navarro et al., 2004; Paz et al., 2008; Shandarin et al., 2012; Codis et al., 2012; Varela et al., 2012; Giahi-Saravani & Schäfer, 2014). The most important model is the model of hierarchical clustering. In this model the large-scale structures in the Universe form "from bottom to up", as a consequence of gravitational novel interactions between galaxies (Peebles, 1969; Doroshkevich, 1973; Dekel, 1985). The original model of hierarchical clustering was significantly improved. In this theory naturally arises the Tidal Torque scenario. Moreover, recently effect of „micro pancake" was also taken into account. Such model is presently accepted as standard model of structure formations.

More generally, the commonly accepted cosmological model is the ΛCDM model. In such model the Universe deems to be spatially flat, as well as homogeneous and isotropic at the same appropriate scale and the structures were formed from the primordial adiabatic, nearly scale invariant Gaussian random fluctuations (Silk, 1968; Peebles & Yu, 1970; Sunyaev & Zeldovich, 1970). This picture is in agreement with both the numerous numerical simulations (Springel et al., 2005; Codis et al., 2012) and the observations. The problem of large structure formation is one of the most

Table 1: The results of numerical simulation - sample of 247 cluster (for real coordinates) each with 2360 galaxies.

	P		δ_D		η	
Test	$\bar{x}$	$\sigma(\bar{x})$	$\bar{x}$	$\sigma(\bar{x})$	$\bar{x}$	$\sigma(\bar{x})$
χ^2	34.9978	0.0172	35.5837	0.0181	37.3439	0.0183
$\Delta_1/\sigma(\Delta_1)$	1.2524	0.0013	1.2571	0.0015	1.4786	0.0015
$\Delta/\sigma(\Delta)$	1.8794	0.0014	1.8870	0.0016	2.1339	0.0015
C	-0.9917	0.0123	-0.6594	0.0130	0.4096	0.0120
λ	0.7708	0.0005	0.8164	0.0007	0.8630	0.0006
$\Delta_{11}/\sigma(\Delta_{11})$	0.0010	0.0020	0.0001	0.0015	0.0021	0.0023

Table 2: The results of numerical simulation - sample of 247 cluster each with 2360 galaxies, fictitious clusters distributed for the whole celestial sphere.

	P		δ_D		η	
Test	$\bar{x}$	$\sigma(\bar{x})$	$\bar{x}$	$\sigma(\bar{x})$	$\bar{x}$	$\sigma(\bar{x})$
χ^2	34.9889	0.0166	35.8522	0.0172	36.2309	0.0181
$\Delta_1/\sigma(\Delta_1)$	1.2520	0.0013	1.2440	0.0013	1.3618	0.0015
$\Delta/\sigma(\Delta)$	1.8771	0.0014	1.8818	0.0014	2.0005	0.0015
C	-1.0114	0.0116	-0.4864	0.0125	-0.3122	0.0124
λ	0.7709	0.0005	0.7790	0.0005	0.8140	0.0006
$\Delta_{11}/\sigma(\Delta_{11})$	0.0022	0.0020	-0.0031	0.0020	0.0005	0.0022

important problem in modern cosmology and extragalactic astronomy. Classical theories of large scale structure formation make different predictions concerning angular momenta of galaxies in structures. Because we know angular momenta of galaxies only for very few galaxies, therefore the orientation of galaxies is investigated. Thus, the investigation of the orientation of galaxies is the ultimate test of a given scenario to compare its predictions with observations (Romanowsky & Fall, 2012; Joachimi et al., 2015). In the present paper, we introduce some improvements of the new method of analysis of the alignment of galaxies in clusters proposed in the papers Godłowski (2012); Panko et al. (2013).

2 Overview

Assuming that galaxy (or galaxy structure) is three axis ellipsoids we determine the position p and inclination i angles. Now we can compute the angles which give the spatial orientation of the normal line to the galaxy (main plane of the structure) in the investigated coordinate system. These are the angles: δ_D giving the information about inclination of the normal line to the main plane of the coordinate system and η giving the information about location of projection of the normal line to the main plane with respect to the X axis (direction towards to the ”zero” initial meridian) (Öpik, 1970; Jaaniste & Saar, 1978; Flin & Godlowski, 1986). These angles give complete information about spatial orientation of galaxy (structures). If we analysing the galactic orientation from deprojection of galaxies images on the celestial sphere we reduce original four-hold ambiguity in the solution for angular momentum to two solutions only, just because of the lack information connected with the direction of the galaxy spin (see Flin & Godlowski, 1986; Godłowski et al., 2010; Godłowski, 2012, for details).

Using the Supergalactic coordinate system (Flin & Godlowski, 1986) based on Sandage & Tammann (1976) the following relations between angles (L, B, P) and

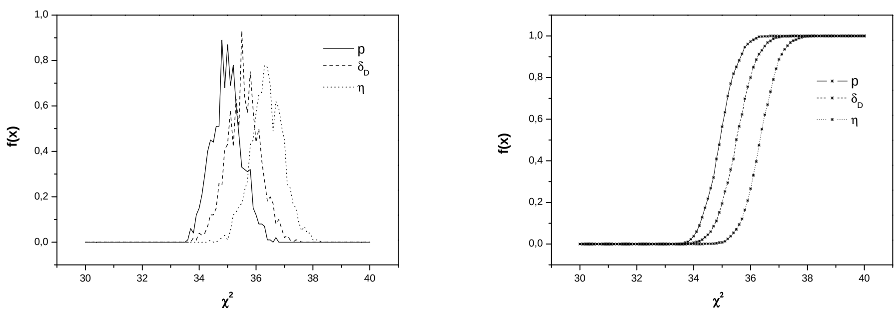

Fig. 1: Differences in Probability Distribution Function (PDF) (left panel) and Cumulative Distribution Function (CDF) (right panel), for angles P, δ_d and η (χ^2 statistics). The figure was obtained from 1000 simulations of sample containing 247 clusters, each with the number of member galaxies the same as in the real cluster.

(δ_D, η) hold:

$$\sin\delta_D = -\cos i \sin B \pm \sin i \cos r \cos B, \tag{1}$$

$$\sin\eta = (\cos\delta_D)^{-1}[-\cos i \cos B \sin L + \sin i(\mp \cos r \sin B \sin L \pm \sin r \cos L)], \tag{2}$$

$$\cos\eta = (\cos\delta_D)^{-1}[-\cos i \cos B \cos L + \sin i(\mp \cos r \sin B \cos L \mp \sin r \sin L)], \tag{3}$$

where $r = P - \pi/2$. As a result of the reduction of our analysis into two solutions it is necessary to consider the sign of the expression: $S = -\cos i \cos B \mp \sin i \cos r \sin B$ and for $S \geq 0$ reverse sign of δ_D respectively, (Godłowski et al., 2010).

The investigation of the orientation of galaxies has nearly 150 years history since Abbe (1875). However, significant progress in such studies of galaxy was made by Hawley & Peebles (1975). Their's method of investigation of galaxies orientation is based on statistical analysis of the distribution of galaxies position angles. The essence of the method is to use three type of statistical tests: χ^2-test, Fourier and First Autocorrelation. In the existing literature, the original methodology of Hawley & Peebles (1975) has been improved and it also has been shown that this methodology can be well used to study the spatial orientation of galaxies planes (Flin & Godlowski, 1986; Kindl, 1987; Godlowski, 1993; Godłowski, 1994; Godlowski & Ostrowski, 1999; Aryal & Saurer, 2000; Godłowski, 2012).

In the papers (Godłowski et al., 2010; Godłowski, 2012; Panko et al., 2013) we have shown that such method could be improved and is very useful for analysis of huge sample of galaxy clusters. Because groups and clusters of galaxies do not rotate (Hwang & Lee, 2007), thus it can be accepted that the total angular momentum of a galaxy structure is mainly related to the galaxies' spins. Moreover, stronger alignment (greater tested statistic) suggests greater total angular momentum of galactic groups or clusters. In the paper Godłowski et al. (2010) it was found that degree of the alignment of galaxies orientations in clusters increasing with theirs richness. In the paper Godłowski (2012) the statistical tests originally proposed by Hawley & Peebles (1975) for analysis of the galactic orientations were analyzed in more detail and some corrections and improvements were proposed. Later, the distributions of the position angles for galaxies in each cluster were analysed. We obtained the value of analysed

Table 3: The statistics of the distributions for position angles for real sample of 247 Abell clusters.

	Equatorial coordinates		Supergalactic coordinates	
Test	$\bar{x}$	$\sigma(\bar{x})$	$\bar{x}$	$\sigma(\bar{x})$
χ^2	36.8591	0.5924	36.7899	0.6315
$\Delta_1/\sigma(\Delta_1)$	1.7046	0.0622	1.7021	0.0626
$\Delta/\sigma(\Delta)$	2.2663	0.0594	2.2746	0.0591
C	1.1940	0.4530	1.1220	0.4237
λ	0.9177	0.0240	0.9138	0.0220
$\Delta_{11}/\sigma(\Delta_{11})$	-0.0005	0.0855	0.0940	0.0924

statistics for each cluster and later we computed the mean value of the analysed statistics. Our null hypothesis H_0 is that mean value of analysed statistics is as expected in the cases of random distribution of analysed angles. The mean value of analysed statistics is compared with theoretical predictions as well as with the results obtained from numerical simulations. We analysed the sample of 247 rich Abell clusters taken from Panko & Flin (2006) catalogue, so the errors of tested statistics significantly decreased. The general result was that the orientations of galaxies in analysed clusters were not random i.e. that there exists an alignment of galaxies in rich Abell galaxy clusters.

The next step is to extend this method for the analysis not only the position angles but also the angles δ_D and η which are giving the spatial orientation of galaxies. The results of our investigation are presented in the Table 1 and Fig. 1. The Fig. 1 was obtained from 1000 simulations of a sample of 247 clusters, each with the number of member galaxies the same as in the real cluster, while the results presented in the Table 1 were extracted from 1000 simulations of a sample of 247 clusters, each with 2360 galaxies. We found significant deviations of mean values of the statistics from expected ones obtained from numerical simulations. From the Figure 1 and Table 1 we can find out that results of the expected value of analysed statistics for angles δ_D and η are larger than that obtained for position angles p. Moreover, from the Table 2 and Table 3 we can figure out that obtained value of statistic are different for angles δ_D and η if we simulate real clusters or fictitious ones distributed for the whole celestial sphere. It is mostly caused of the fact that during the process of deprojection of the spatial orientation of galaxies from its optical images we obtain two possible orientations - see equations 1-3. From analysis of these equations it is easy to see that both solutions are not independent and as a result the distribution of analysed statistics is modified and must be obtained from numerical simulations. The analysis of the position angles (Table 3) shows that orientation of galaxies in analysed sample of 247 rich Abell clusters are not random, i.e we observed the alignment of galaxies in rich Abell galaxy cluster. However, the effect mentioned above should be taken into account during future detailed investigations of spatial orientation in clusters.

3 Conclusions

In the present paper preliminary results of improved analysis of the alignment in Abell Galaxy Cluster were presented. The alignment of galaxies in rich Abell galaxy clusters is observed. We confirmed Panko et al. (2013) suggestions that expected values of analysed statistics for the angles giving spatial orientation of galaxies, δ_D and η are greater than that obtained for the position angles of major axis of galaxies. Such effect must be taken into account during future detailed analysis of the spatial orientations of galaxies in clusters.

The crucial goal of our investigations is to discriminate among different models of galaxy formation. For that, in the future investigations we should use novel theoretical approach Stephanovich & Godłowski (2015) in which the distribution function of dynamic characteristics of galaxies ensembles is calculated via tidal (shape-distorting) quadrupolar (and also higher multipolar) interaction between the galaxies. This function, among other things, might be used to better statistical treatment of observational data, which permit to discriminate observationally the relevance of available theories of galaxies formation. The calculation of the average galaxies angular momenta with the help of above distribution function permit to study theoretically their orientations. This theoretical predictions could be compared with observational results. This is important as an investigation of the orientation of galaxies in clusters is regarded as a standard test of theories of galaxy and large-scale structure formation (Romanowsky & Fall, 2012; Joachimi et al., 2015).

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