SOME OBSERVATIONAL ASPECTS OF THE ORIENTATION OF GALAXIES*

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We investigated the sample of galaxies belonging to the Tully groups of galaxies. We analyzed the orientation of galaxies inside the group. We did not found significant deviation from isotropy both in orientation of position angles or the angles δ_D and η giving the spatial orientation of galaxy planes. Moreover, we analyzed consequences of different approximation of "true shape" of galaxies and pointed to possible influence of this problem on the investigation of spatial orientation of galaxies. Implications of the obtained results for the theory of galaxy formation were discussed as well.

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1. Introduction

The problem of structure formation in the Universe is one of the most important problems of modern extragalactic astronomy and cosmology. One of interesting aspects of this problem is the analysis of orientation of galaxies inside the structures. The very important question is if there exists dependence of the alignment on the mass of analyzed structures. It is because the investigation of orientation of galaxies planes is regarded as a standard test of galaxies formation scenarios [1, 2, 3, 4, 5, 6, 7, 8, 9].

There was a lot of studies of the orientations of galaxies inside clusters (see [10] for the latest review). Godłowski *et al.* [11] suggested that alignment of galaxies in cluster should increase with the number of objects in a particular cluster. This suggestion was confirmed by Aryal *et al.* [12], based on the series of papers [13, 14, 15]. However both [11] and [12] analyses were qualitative only. Therefore, Godłowski *et al.* [16] analyzed a sample of 247 rich Abell clusters using statistical tests and found that alignment increased

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with the richness of the clusters. The analysis of the orientation of galaxies in poor galaxy structures — Tully groups of galaxies, was performed by Godłowski *et al.* [11]. In this paper, it was found that the group does not exhibit clear evidence for existence of alignment in the investigated structures. However, they concluded that observational effect generated by the process of deprojection of galaxies [17], later confirmed by [18, 19], masks to the high degree any possible alignment during analysis of the spatial orientation of galaxies in clusters. For these reasons we analyzed the orientation of galaxy in Tully galaxy group in more details.

2. Observational data

The aim of our work is to study the alignment of galaxies in galaxy groups. Groups were taken from Tully Nearby Galaxies (NBG) Catalog [20]. This Catalog contains 2367 galaxies with radial velocities lower than 3000 km s^{-1}. Tully Catalog provides relatively uniform coverage of entire unobscured sky [21]. Galaxies position angles were taken from [22, 23, 24, 25] while some missing measurements were made on PSS prints by Flin [26]. The NBG Catalog gives the group affiliation for the galaxies belonging to the catalog. The groups extracted from the NBG Catalog are one of the best selections with precise criterion of groups membership. Moreover, the galaxy distances are very well and in uniform manner determined. As a result, the lists of galaxies belonging to the particular groups are free from the background objects which is crucial in such type of the analysis. From the NBG Catalog we extracted structures having at least 40 members.

3. Methods of the analysis and results

We studied the alignment of galaxies in Tully groups of galaxies belonging to the Local Supercluster (LSC). Till now two main methods for the study of galaxy orientation have been proposed. In the first one [27], the distribution of the position angle of the galactic image major axis was analyzed. In this approach, face-on and nearly face-on galaxies were excluded from the analysis and only galaxies with axial ratio $d/D \leq 0.75$ were taken into consideration. The second approach, based on the de-projection of the galaxy images, allowed us to use also the face-on galaxies, This method was originally proposed by Öpik [28], applied by Jaaniste and Sarr [29] and significantly modified by Flin and Godłowski [26, 30, 31, 32, 33, 34]. In this method, the galaxy's inclination with respect to the observer's line of sight i is considered. In the Tully NBG Catalog [20] the inclination angle was calculated according to formula $i = \cos^{-1}\left(q^2 - q_0^2\right)/\left(1 - q_0^2\right)^{-1/2} + 3^0$, where $q = d/D$ is the ratio of minor to major axis diameters and q_0 is "true" axial ratio. Tully used standard value $q_0 = 0.2$. One should note that above formula is the modified Holmberg's [35] formula valid for oblate spheroids. For each galaxy, two angles are determined: δ_D — the angle between the normal to the galaxy plane and the main plane of the coordinate system, and η — the angle between the projection of this normal onto the main plane and the direction towards the zero initial meridian. Using the Supergalactic coordinate system (Flin and Godłowski [30] based on [36]) the following relations hold between angles (L, B, P) and (δ_D, η)

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

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

where $r = P - \pi/2$.

In order to detect non-random effects in the distribution of the investigated angles: δ_D, η and P, we divided the entire range of the analyzed angles into 18 bins and carried out three different statistical tests. These tests were: the χ^2 test, the autocorrelation test and the Fourier test [16, 27, 33, 34, 37]. For $n = 18$ the χ^2 test yields critical value 27.59 (at the significance level $\alpha = 0.05$) while critical value for autocorrelation test is $C_{\rm cr} \approx 6.89$. The last value is obtained from numerical simulations using the method described by Godłowski [37]. The isotropy of the resultant distributions of the investigated angles was also analyzed using Kolmogorov–Smirnov test (KS test). We assumed that the theoretical, random distribution contains the same number of objects as the observed one. In order to reject the H_0 hypothesis, that the distribution is random one, the value of observed statistics λ should be greater than $\lambda_{\rm cr} = 1.358$ (for $\alpha = 0.05$). One should note however, that especially in the case of position angles, the number of analyzed galaxies is sometimes small and does not satisfy theoretical tests conditions. It is the reason that we repeated our analysis with different numbers of bins, founding insignificant differences in these cases.

At first, following Godłowski *et al.* [11] but adding the KS test, we analyzed orientation of galaxies in Tully groups using, for obtaining δ_D and η angles, inclinations angles taken directly from NBG Catalog [20] (sample A). The results were presented in Tables I–III. Analysis of the supergalactic position angles showed that only one group (61) exhibits alignment of galaxies. Analysis of the distribution of the angles giving spatial orientation of galaxies (δ_D and η) seems to show weak alignment. For δ_D angle three tests showed that the distribution is non random in the case of the clusters 11, 31 and 51. Two tests showed nonrandomness in the case of clusters 41 and 52. For η angle three tests showed alignment in the case of clusters 11, 12, 41, 52 and 64. Two tests showed it in the case of clusters 31 and 51.

TABLE I

Test for isotropy of the orientations of galaxy plane. The distribution of the angle δ of galaxies, inclination taken directly from NGC Catalog.

Angle	Group	N	χ^2	C	$P(\Delta_1)$	Δ_{11}	$\sigma(\Delta_{11})$	λ
	11	626	62.8	9.50	.000	−.237	.058	1.20
	12	332	25.7	−11.48	.299	−.125	.080	0.55
	13	128	29.7	−6.94	.891	0.002	.129	0.62
	14	426	24.0	3.52	.154	−.120	.071	0.78
	15	130	13.1	−1.88	.737	−.004	.128	0.59
	17	80	13.8	−5.50	.569	−.100	.164	0.82
	21	248	14.2	0.24	.065	−.035	.093	1.14
	22	126	7.0	0.68	.496	0.098	.130	0.62
δ	23	100	17.0	−1.82	.607	0.140	.146	0.47
	31	210	33.7	15.98	.000	0.137	.101	1.79
	41	192	22.8	6.54	.020	−.004	.106	1.37
	42	230	24.7	−3.78	.320	0.056	.096	0.75
	44	80	26.7	7.95	.024	−.200	.164	1.34
	51	228	29.6	−0.41	.009	0.093	.097	1.44
	52	172	21.6	3.04	.005	−.203	.112	1.42
	53	260	13.3	−3.29	.492	−.055	.091	0.62
	61	258	19.9	−3.13	.825	−.049	.091	0.62
	64	102	28.7	−7.54	.113	0.080	.145	0.84

TABLE II

Test for isotropy of the orientations of galaxy plane. The distribution of the angle η of galaxies, inclination taken directly from NGC Catalog.

Angle	Group	N	χ^2	C	$P(\Delta_1)$	Δ_{11}	$\sigma(\Delta_{11})$	λ
	11	626	60.0	5.96	.000	0.304	.057	2.00
	12	332	28.5	7.56	.001	−.069	.078	1.70
	13	128	25.6	2.78	.079	0.242	.125	0.77
	14	426	27.4	6.63	.090	0.055	.069	1.00
	15	130	22.9	2.51	.764	0.036	.124	0.91
	17	80	13.1	−5.97	.470	−.059	.158	0.46
	21	248	26.9	−3.55	.054	0.058	.090	1.23
	22	126	11.7	5.57	.177	0.194	.126	0.98
η	23	100	20.2	−0.10	.081	−.164	.141	1.09
	31	210	24.0	0.43	.046	0.194	.098	1.56
	41	192	27.2	10.22	.001	0.300	.102	1.95
	42	230	15.9	3.30	.033	0.036	.093	1.24
	44	80	20.4	−3.05	.226	0.148	.158	0.78
	51	228	30.6	−5.37	.042	0.218	.094	1.15
	52	172	38.1	12.29	.001	0.212	.108	1.92
	53	260	12.2	−8.28	.816	0.008	.088	0.34
	61	258	23.7	−12.56	.549	0.091	.088	0.64
	64	102	50.1	−3.53	.002	0.402	.140	1.88

TABLE III

Test for isotropy of the distribution of supergalactic position angles P of galaxies.

Angle	Group	N	χ^2	C	$P(\Delta_1)$	Δ_{11}	$\sigma(\Delta_{11})$	λ
	11	185	22.7	−11.42	.728	0.081	.104	0.53
	12	106	17.6	−1.57	.198	−.083	.137	0.88
	13	50	13.4	−2.48	.714	−.056	.200	0.41
	14	133	14.9	−1.05	.990	−.011	.123	0.49
	15	48	11.3	−0.75	.185	−.006	.204	1.06
	17	22	10.7	−5.64	.727	−.152	.302	0.62
	21	85	13.5	−2.84	.878	−.058	.153	0.67
	22	43	16.0	−1.98	.910	−.089	.216	0.63
P	23	33	12.3	0.27	.230	−.337	.246	0.81
	31	63	20.1	1.00	.729	0.081	.178	0.82
	41	54	20.0	10.67	.595	−.112	.192	1.09
	42	71	19.0	1.51	.124	−.254	.168	0.91
	44	25	18.9	1.64	.367	0.161	.283	0.98
	51	69	23.1	3.00	.576	−.176	.170	0.88
	52	50	14.8	−0.32	.631	0.154	.200	0.77
	53	88	17.5	2.82	.080	0.243	.151	1.36
	61	85	27.9	6.48	.007	−.116	.153	1.68
	64	31	18.4	2.10	.295	−.397	.254	0.91

For more detailed analysis we used the method described in [37]. The question which arose is if we could say that we found an alignment in the analyzed sample of 18 Tully groups of galaxies. So we computed the mean value and variance of analyzed statistics: χ^2, $\Delta_1/\sigma(\Delta_1)$, $\Delta/\sigma(\Delta)$ (*i.e.* the same statistics as was analyzed in [16]) for our sample of 18 groups and compared it with results of numerical simulations. We performed 1000 simulations of 18 fictitious clusters, each with number of randomly oriented, members galaxies, the same as in real clusters. In Table IV we present, obtained from numerical simulations average values of the analyzed statistics, their standard deviations, standard deviations in the sample as well as their standard deviations for distribution of P angles. One should note that there are some differences in results of numerical simulations for P, δ_D and η angles but it does not change our further conclusions. The mean values

TABLE IV

The results of numerical simulations for positions angles P.

Test	$\bar{x}$	$\sigma(x)$	$\sigma(\bar{x})$	$\sigma(\sigma(x))$
χ^2	16.9524	1.4592	0.0461	0.0326
$\Delta_1/\sigma(\Delta_1)$	1.2513	0.1543	0.0048	0.0034
$\Delta/\sigma(\Delta)$	1.8772	0.1581	0.0050	0.0035

and variance of analyzed statistics for sample of real clusters are presented in Table V. On can show that (for sample A) analysis of the position angles does not show significant deviation from the values expected in the case of random distributions, while it seems that analysis of angles δ_D and η shows existence of alignment at the 2σ level (with exception of $\Delta/\sigma(\Delta)$ statistics for δ_D angle). However, below we will argue against such interpretation.

TABLE V

The statistics of the observed distributions for real clusters.

		P		δ_D		η	
Sample	Test	$\bar{x}$	$\sigma(x)$	$\bar{x}$	$\sigma(x)$	$\bar{x}$	$\sigma(x)$
A	χ^2	17.338	1.061	23.794	2.853	26.583	2.946
	$\Delta_1/\sigma(\Delta_1)$	1.282	0.177	1.847	0.257	2.443	0.287
	$\Delta/\sigma(\Delta)$	2.112	0.209	2.328	0.256	2.910	0.272
B	χ^2	16.800	1.152	18.700	1.332	20.188	2.166
	$\Delta_1/\sigma(\Delta_1)$	1.218	0.176	1.420	0.169	1.554	0.233
	$\Delta/\sigma(\Delta)$	2.081	0.218	2.076	0.165	2.385	0.302

The Tully groups were analyzed also by Godłowski and Ostrowski [17]. For every cluster the parameter Δ_{11} describing the galactic axes alignment with respect to a chosen cluster pole, divided by its formal error $\sigma(\Delta_{11})$ ($s \equiv \Delta_{11}/\sigma(\Delta_{11})$) were mapped. The cluster pole coordinates change along the entire celestial sphere. The resulting maps were analyzed for correlations of their maxima with important points on the maps (see Fig. 1 for details). It was found that maxima correlated well with the line of sight direction. Godłowski and Ostrowski [17] concluded that the strong systematic effect, generated by the process of galactic axis de-projection from its optical image, is present in the catalogue data. The example of that effect is presented in Fig. 1. To avoid possible influence of global alignment inside LS, we choose for presentation the cluster 12 (Ursa Major Cloud) because it is far from the center of the Local Supercluster (*i.e.* Virgo Cluster). To remove the above effect we should avoid the assumption that the "true" axial ratio is $q_0 = 0.2$, which is a rather poor approximation, especially for non-spiral galaxies. Fortunately, NBG Catalog contains morphological types of galaxies. These allowed us to use different values of q_0 depending on morphological type [38]. Now, with help of Fouque and Paturel [39] formulae, which convert q to standard photometrical axial ratios, we compute new inclination angle i for all galaxies in NGB catalog. We repeated our investigation with that "new" sample of galaxies (sample B). As one can see from right panel of Fig. 1, the "line of sight" effect disappeared which shows that our procedure for

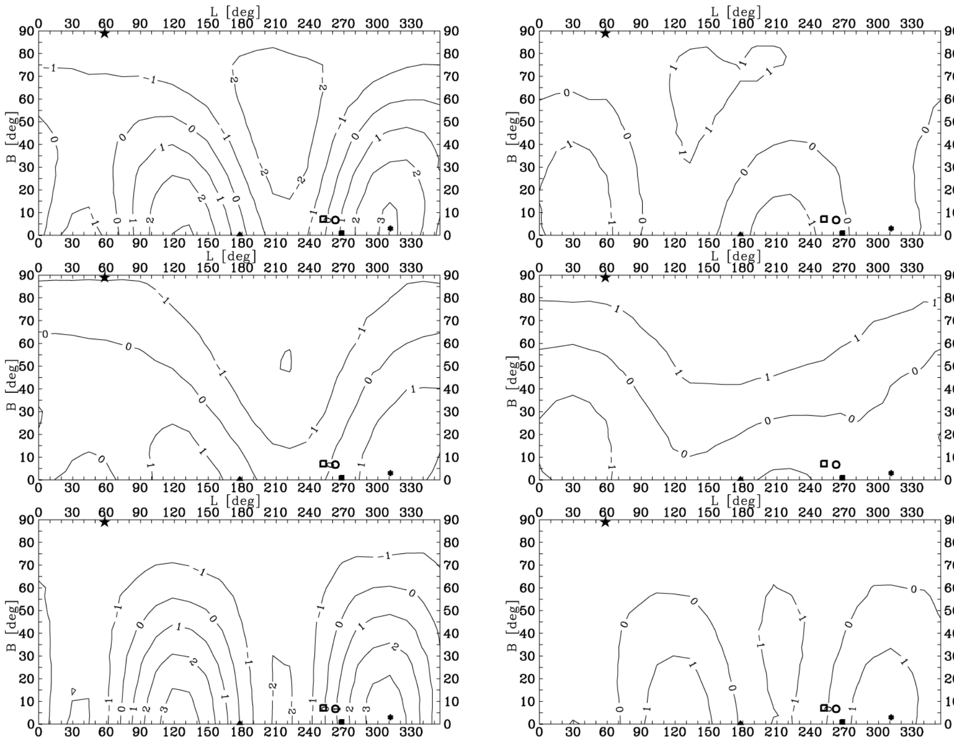

Fig. 1. Maps of $s \equiv \Delta_{11}/\sigma(\Delta_{11})$ *versus* the chosen cluster pole supergalactic co-ordinates (L, B) for the cluster 12. In the maps, results for Tully data are shown on the left, while results obtained from of HHD and FP corrections are given on the right. The maps are presented for ALL cluster galaxies (upper panel), for S (middle panel) and NS (bottom panel) sub-samples. In the map we indicate the important directions, as seen from the centre of the considered cluster: (1) three cluster poles (full star, square and triangle), (2) the direction to the Local Supercluster centre (open circle), (3) the direction of the Virgo A cluster centre (open square) and (4) the line of sight from the Earth (asterisk).

computation of the inclination angles are much better than the previous one. From Table VI and Table VII we can show that during analysis of the spatial orientation of galaxies, the alignment is observed only in the case of η angle for clusters 11 and 41 (Virgo Cluster and Virgo — Libra Cloud). Of course, our procedure does not change position angles. In Table VIII we presented analyzes of the distribution of P, where only galaxies with the certainly measure positions angles were taken into account. On can show (Table V, sample B) that now the mean value of analyzed statistics does not exhibit any significant deviation from the values expected in the case of random distributions. The above results allowed us to conclude that we did not observe any significant alignment for Tully groups of galaxies.

TABLE VI

Test for isotropy of the orientations of galaxy plane. The distribution of the angle δ of galaxies, inclination obtained according to HHD and FP corrections.

Angle	Group	N	χ^2	C	$P(\Delta_1)$	Δ_{11}	$\sigma(\Delta_{11})$	λ
	11	626	14.3	−2.46	.504	−.068	.058	0.39
	12	332	12.4	2.49	.744	0.059	.080	0.37
	13	128	8.7	0.86	.387	0.161	.129	0.54
	14	426	22.7	1.50	.654	−.063	.071	0.52
	15	130	26.2	4.40	.025	0.243	.128	1.25
	17	80	7.0	−1.57	.949	−.018	.164	0.48
	21	248	19.7	6.05	.575	0.067	.093	0.85
	22	126	17.9	1.77	.037	0.187	.130	1.30
δ	23	100	22.1	−3.00	.150	0.275	.146	0.71
	31	210	19.1	3.90	.049	0.050	.101	0.74
	41	192	20.9	−4.77	.354	0.134	.106	0.69
	42	230	18.3	−4.08	.419	−.091	.096	0.86
	44	80	23.9	0.74	.525	−.104	.164	0.93
	51	228	18.3	3.40	.793	0.031	.097	0.61
	52	172	20.7	4.97	.005	−.169	.112	1.53
	53	260	13.2	−1.46	.669	−.061	.091	0.62
	61	258	25.3	−1.26	.359	−4.020	.091	1.03
	64	102	25.9	−1.99	.146	0.008	.145	0.78

TABLE VII

Test for isotropy of the orientations of galaxy plane. The distribution of the angle η of galaxies, inclination obtained according to HHD and FP corrections.

Angle	Group	N	χ^2	C	$P(\Delta_1)$	Δ_{11}	$\sigma(\Delta_{11})$	λ
	11	626	44.1	13.00	.000	0.215	.057	1.37
	12	332	21.3	3.87	.075	-.070	.078	1.65
	13	128	18.3	5.17	.272	0.191	.125	0.67
	14	426	8.5	0.34	.418	0.038	.069	0.45
	15	130	22.0	−11.48	.651	0.089	.124	0.57
	17	80	8.2	−3.05	.603	−.103	.158	0.40
	21	248	15.8	−6.45	.718	0.015	.090	0.75
	22	126	14.6	1.00	.767	0.092	.126	0.53
η	23	100	7.3	−1.18	.809	0.009	.141	0.40
	31	210	20.2	0.17	.047	0.226	.098	0.81
	41	192	38.3	20.16	.007	0.099	.102	1.61
	42	230	20.6	4.94	.729	0.074	.093	0.59
	44	80	19.5	−3.95	.763	−.013	.158	0.55
	51	228	20.8	2.61	.736	0.067	.094	0.66
	52	172	17.6	−0.37	.085	0.100	.108	0.99
	53	260	19.3	−3.50	.888	−.005	.088	0.51
	61	258	23.7	2.09	.045	0.122	.088	1.22
	64	102	23.3	−5.65	.289	0.204	.140	0.76

TABLE VIII

Test for isotropy of the distribution of supergalactic position angles P of galaxies. Only galaxies with certain measure P are taken into account.

Angle	Group	N	χ^2	C	$P(\Delta_1)$	Δ_{11}	$\sigma(\Delta_{11})$	λ
	11	143	17.7	−9.32	.991	−.001	.118	0.40
	12	96	19.5	0.19	.113	−.071	.144	0.99
	13	40	16.7	1.40	.805	−.142	.224	0.81
	14	114	14.2	2.21	.943	−.045	.132	0.44
	15	42	12.0	−0.86	.201	0.057	.218	1.03
	17	21	10.7	−5.57	.656	−.241	.309	0.58
	21	76	11.2	−3.53	.859	−.059	.162	0.55
	22	37	15.1	−1.49	.997	−.003	.232	0.57
P	23	33	12.3	0.27	.230	−.337	.246	0.81
	31	58	23.3	4.07	.444	0.080	.186	0.83
	41	46	21.3	9.17	.481	−.121	.209	1.08
	42	64	18.1	2.38	.075	−.282	.177	1.04
	44	21	19.3	−2.14	.352	0.245	.309	0.84
	51	60	21.0	0.00	.759	−.110	.183	0.82
	52	32	8.5	−1.63	.788	0.170	.250	0.37
	53	84	16.3	0.86	.135	0.203	.154	1.24
	61	78	27.7	1.38	.040	−.086	.160	1.47
	64	25	17.5	3.08	.331	−.362	.283	1.14

4. Discussion and conclusions

We investigated the orientation of galaxies inside 18 Tully groups of galaxies belonging to the Local Supercluster, not founding any significant alignment. So we conclude that orientations of galaxies in the Tully groups are random. We also analyzed observational effect generated by the process of deprojection of galaxies found by Godłowski and Ostrowski [17], which masks to high degree any possible alignment during analysis of spatial orientation of galaxies in clusters. We showed that using "true shape" of galaxies q_0 depending on morphological type according to Heidmann *et al.* [38] with help of Fouque and Paturel [39] corrections of q to standard photometrical axial ratios, allowed us to avoid this problem. This gives much more powerful investigation of the spatial orientation of galaxies.

In our previous papers, we found that in the sample of 247 rich Abell galaxy clusters we observed an alignment, which increased with the cluster richness [16, 37]. Now, we found that the orientation of galaxies inside the poor galaxy structure is random. It confirms our suggestion that alignment of galaxies increases with the mass of the structures [10]. Usually, such dependence between the angular momentum and the mass of the structure is presented as empirical relation $J \sim M^{5/3}$ [40, 41, 42, 43]. The observed relation between mass of the galaxy structure and the alignment is compatible with the prediction of the Li model [44] in which galaxies are forming in the rotating universe. However, in our opinion, it is due to tidal torque, as suggested by [45, 46]. Also the results of the analysis of the linear tidal torque theory which noticed the connection of the alignment with the considered scale of the structure is pointing in the same direction [47, 48].

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