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A NEW METHOD OF INVESTIGATION OF THE ORIENTATION OF GALAXIES IN CLUSTERS IN LACK OF INFORMATION ABOUT THEIR MORPHOLOGICAL TYPES

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ABSTRACT. The problem of the formation of structures in the universe is one of the most important issues of modern extragalactic astronomy and cosmology. The tool enabling the verification of a particular formation scenario is analysis the spatial orientation of the galaxies from deprojection of their images. Obtaining correct analysis results obliges to take into account the fact that galaxies are oblate spheroids with the real axis ratio depending on the morphological type, which, however, is not given in most of the currently available astronomical data. According to the approach used in the new method of investigation, on the basis of estimated frequencies of occurrence of given morphological types, obtained using sufficiently numerous observational data, simulations are performed, which enable to recognize new angle distributions used in orientation studies. These distributions already contain information on the frequency of the appearance of galaxies of particular morphological types in clusters, allowing for more accurate results of the statistical tests carried out during the analysis. The method is an extension of results developed in Godłowski 2012 and Pajowska et al. 2019.

Keywords: Galaxies: clusters, orientation, morphological types.

АНОТАЦІЯ. Проблема формування структур у Всесвіті є однією з найважливіших проблем сучасної позагалактичної астрономії та космології. Інструментом, що дозволяє перевірити заданий сценарій, є аналіз просторової орієнтації галактик на основі депроекції їх зображень. Отримання правильних результатів аналізу вимагає врахування того факту, що галактики є сплюснутими сфероїдами, фактичне співвідношення осей яких залежить від морфологічного типу, що не передбачено в більшості наявних на даний момент астрономічних даних. Відповідно до нового підходу, використаного в новому методі, на основі оцінених частот зустрічальності заданих морфологічних типів, отриманих з використанням достатньо великої кількості даних спостережень, проводяться моделювання, які дозволяють отримати нові кутові розподіли, які використовуються в орієнтаційних дослідженнях. Ці розподіли вже містять інформацію про частоту появи певних морфологічних типів у скупченнях галактик, що дозволяє отримувати точніші результати статистичних перевірок, проведених під час аналізу. Цей метод є розширенням результатів, отриманих Godłowski 2012 та Pajowska та ін 2019 рік.

Ключові слова: Галактики: скупчення, орієнтація, морфологічні типи.

1. Introduction

The state of knowledge regarding the formation of structures in the Universe has developed significantly, but this problem still remains one of the most important issues of modern extragalactic astronomy and cosmology. Over the years, the original theories of the formation of galaxies and their structures have been verified many times and have also undergone modifications, resulting in the creation of new versions of the models. The model of hierarchical clustering has remained valid and has been significantly improved.

According to the commonly accepted ΛCDM cosmological model, the Universe is considered to be spatially flat, isotropic and homogeneous on an appropriately large scale, and structures are formed from primordial, adiabatic, self-scaling Gaussian fluctuations (Silk 1968, Peebles & Yu 1970, Sunyaev & Zeldovich 1970, Stephanovich & Godłowski 2015). A standard test of scenarios for the formation of galaxies and their structures, enabling comparison of predicted theoretical results with observations, is the investigation of galaxy orientation. This results from different predictions regarding the distributions of galaxy angular momentum postulated by individual scenarios of the formation and evolution of cosmic structures (Romanowsky & Fall 2012; Joachimi et al. 2015; Kiessling et al. 2015). These analyses assume that normals to the galaxies planes are their rotation axes, which is especially true for spiral galaxies.

The first application of the research method that became a standard tool for searching galaxy alignments was realized in the paper of Hawley and Peebles (1975). It consisted a statistical analysis of the galaxies angular momenta based on the observed angles of the main axes of the galaxy image, in order to detect possible deviations from the isotropic distribution. However, because the direction of the angular momentum is perpendicular to the direction of the major galaxy axis, the original version of the method only allowed for the analysis of side-viewed galaxies.

The use of galaxies with all possible orientations and locations on the celestial sphere in the study is possible applying a method based on the deprojection of galaxy images, proposed by Öpik (1970), applied by Jaaniste and Saar (Jaaniste 1977, Jaaniste & Sarr 1978) and significantly modified by Flin and Godłowski (Flin & Godłowski 1986, Godłowski 2012, Pajowska, Godłowski et. al 2019). For this purpose, this method, in addition to the positional angles of galaxies, also uses their ellipticities. Obtaining correct results, however, obliges one to take into account the Holmberg effect in the analysis, which consists of the fact that the measured, especially optical, ellipticity of the image of galaxies differs from the true ellipticity of the image (Holmberg 1946, 1958, 1975, Fouque & Paturel 1985), and the fact that galaxies are flattened spheroids with the actual axis ratio depending on their morphological type.

Nowadays, it is becoming increasingly common practice to make high-quality, readily usable astronomical data widely available. Sky surveys such as SDSS, DESI, Euclid, and Kilo-Degree Survey provide the opportunity to create catalogs of galaxy clusters and then conduct studies of the orientation of their members. Like most astronomical data currently published, these surveys do not contain information about the morphological types of galaxies. For this reason, in the case of studies carried out using data that did not contain information about the values of the actual axis ratio of galaxies, the average value of this parameter was used. However, in some cases this solution is insufficient (see Godłowski 2011 and Pajowska 2012). This paper presents a new, improved method of investigation the orientation of galaxies in clusters, allowing for more accurate analysis results using the estimated frequencies of occurrence of given morphological types.

2. New method of investigation of the orientation of galaxies in clusters

The new method of investigation the orientation of galaxies in clusters is an extension of the approach presented in the papers of Flin and Godłowski (1986), Godłowski (2012) and Pajowska et al. (2019). The method calculates two angles determining the spatial orientation of galaxies. The first is the “polar” angle δ_D - the angle between the normal to the galaxy plane and the main plane of the coordinate system. The second one, the “azimuth” angle η, describes the direction between the projection of this normal onto the main plane and the direction towards the zero initial meridian. In the case of a supergalactic coordinate system, the main plane is the supergalactic equator, and these angles can be expressed as the relationship between the latitude and longitude angles, B and L, the position angle P, and the inclination angle i (Figure 1). Deprojection of galaxy images on the celestial sphere gives four solutions for the angular momentum vector. In the absence of information about the direction of galaxy rotation, it is sufficient to examine only the directions perpendicular to the galaxy plane. This fact transfer into the need to take into account two possible settings of galaxies. The formulas for calculating the δ_D and η angles are expressed by the following relationships:

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

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

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

where $r = P - \frac{\pi}{2}$. As a result of the reduction of the analysis into two solutions only, it is necessary to consider the sign of the expression: $S = -\cos i \cos B \mp \sin i \cos r \sin B$ and for $S > 0$ should be reversed the sign of δ_D respectively. In the investigation is an uniform distribution of angles on the sphere. For this reason, numerous ranges of δ_D and η angles should be characterized by cosine and uniform distributions, respectively. As part of the study, using statistical methods, the obtained real distributions of these angles are confronted with the theoretical distributions.

The inclination angle can be computed from the image of the galaxy using Holmberg’s formula for oblate spheroids (Holmberg 1946)

$$i = \cos^{-1}\left(\sqrt{\frac{q^2 - q_0^2}{1 - q_0^2}}\right), \tag{4}$$

where $q = \frac{d}{D}$ is the ratio of the minor to the major axis diameters, and q_0 is the ”true” axial ratio.

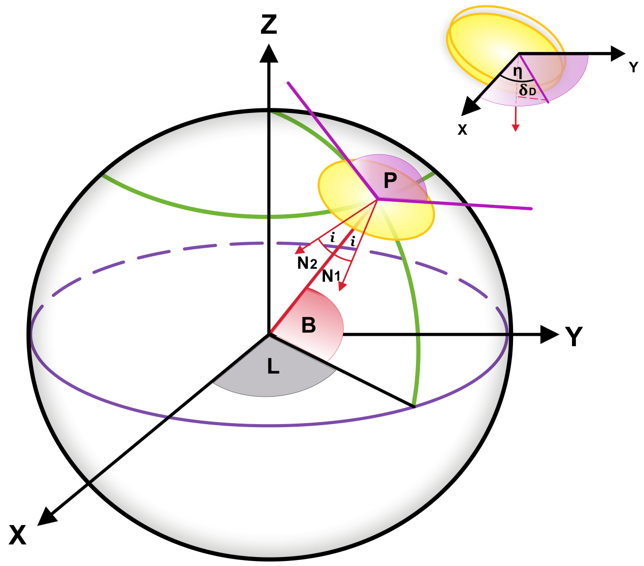

Figure 1: A schematic illustration of angles δ_D (the polar angle between the normal to the galaxy plane and the main plane of the coordinate system) and η (the azimuth angle between the projection of this normal onto the main plane and the direction towards the zero initial meridian). The angle of inclination i is the angle between the normal to the plane of the galaxy a observer's line of sight, while P is the angle of the position in the frame of reference. N_1 and N_2 are possible positions of the normal to galaxy plane directed line segment inside the sphere. L and B are the longitude and latitude of the reference coordinate system.

Each morphological type, using the Heidmann, Heidmann and de Vaucouleurs (HHD) approach, can be assigned a corresponding value of the q_0 parameter. In the absence of information about the morphological types of galaxies, $q_0 = 0.2$ is used (described in Pajowska et al. 2019). An alternative approach was used by Tully in his catalogue (Tully 1988), taking this constant value of q0 and adding 3° to the calculated inclination angle to compensate for the failure to take into account different morphological types of galaxies $i = \cos^{-1}\left(\sqrt{(q^2 - 0.2^2)/(1 - 0.2^2)}\right) + 3°$.

According to the approach presented in the new method, the lack of information about the morphology of galaxies can be compensated by using the estimated frequencies of occurrence of given morphological types. Assuming an isotropic distribution of normals to the plane of the galaxy in space, an isotropic random distribution of inclination angles is generated. By using the known frequencies of occurrence of given morphological types and the HHD approach for parameter q_0, the Holmberg formula can be reversed and a new "isotropic" distribution of the "observed" axial ratio q can be obtained. This allows to perform numerical simulations for the examined clusters of galaxies, which enable to learn new values of the inclination angle i through one of the formulas. Using these new values of i, new values of angles δ_D and η can then be calculate. "Theoretical isotropic distributions" of angles δ_D and η contain information about the frequency of appearance of galaxies of particular morphological types in clusters.

3. Application of a new method of investigation

Determining the effectiveness of a new method requires testing it under controlled test conditions. For this purpose, the Tully Nearby Gaslaxies (NBG) Catalog (Tully 1988) was used to implement the method, which contains all the necessary information about galaxies, in particular about their morphological types and affiliation to structures. It has been carefully screened for the completeness of the sample and the removal of non-galactic objects from it. The galaxies included in the catalog are devoid of background objects and provide relatively even coverage of the entire unobstructed sky (Tully 1987). The use of the Tully's catalog in other research works (Godłowski & Flin 2010, Godłowski 2011, Pajowska 2012) also makes it possible to indicate the correlation of the obtained results.

To implement the method from the NBG Catalog, 18 groups with at least 40 members were used. The actual coordinates of the galaxies were used to calculate the δ_D and η angles. The information on the morphology of galaxies contained in the catalog was used to calculate the estimated frequencies of occurrence of given morphological types.

To analyze the distribution of δ_D and η angles, statistical methods described in the paper Pajowska et al. 2019 were used: the χ^2 test, the First Autocorrelation test, the Fourier test, the Kolmogorov-Smirnov test, the Cramer-von Mises test and the Watson test. The first three of these tests were originally proposed in the paper of Hawley & Peebles 1975. The analyzed range of the test angle theta (equal to $\delta_D + \frac{\pi}{2}$ or η) is divided into a particular number of equal to the width of bins, in this case $n = 18$.

The χ^2 test uses the statistic:

$$\chi^2 = \sum_{k=1}^{n} \frac{(N_k - Np_k)^2}{Np_k} = \sum_{k=1}^{n} \frac{(N_k - N_{0,k})^2}{N_{0,k}} \quad (5)$$

where N is the total number of galaxies in the cluster, p_k is the probability that the selected galaxy will fall into the k-th bin, and N_k and $N_{0,k}$ are the obtained and expected numbers of galaxies in the k-th bin.

The First Autocorrelation test determines the correlations between galaxy numbers in neighboring angle bins. The statistic C is given by:

$$C = \sum_{k=1}^{n} \frac{(N_k - N_{0,k})(N_{k+1} - N_{0,k+1})}{[N_{0,k}N_{0,k+1}]^{\frac{1}{2}}} \tag{6}$$

where $N_{n+1} = N_1$.

The Fourier test was significantly improved by Godłowski (2012). In the test, deviation from isotropy is a slowly varying function of the angle θ, according to the relationship:

$$\begin{aligned} N_k = N_{0,k}(1 + \Delta_{11}\cos 2\theta_k + \Delta_{21}\sin 2\theta_k + \\ + \Delta_{12}\cos 4\theta_k + \Delta_{22}\sin 4\theta_k + \ldots) \end{aligned} \tag{7}$$

In that case all $N_{0,k}$ are equal. The Fourier coefficients are given by formulas:

$$\Delta_{1J} = \frac{\sum_{k=1}^{n}(N_k - N_{0,k})\cos 2J\theta_k}{\sum_{k=1}^{n} N_{0,k}\cos^2 2J\theta_k} \tag{8}$$

$$\Delta_{2J} = \frac{\sum_{k=1}^{n}(N_k - N_{0,k})\sin 2J\theta_k}{\sum_{k=1}^{n} N_{0,k}\sin^2 2J\theta_k} \tag{9}$$

with standard deviations given by:

$$\sigma(\Delta_{1J}) = \left(\sum_{k=1}^{n} N_{0,k}\cos^2 2J\theta_k\right)^{-\frac{1}{2}} \tag{10}$$

$$\sigma(\Delta_{2J}) = \left(\sum_{k=1}^{n} N_{0,k}\sin^2 2J\theta_k\right)^{-\frac{1}{2}} \tag{11}$$

The probability that the amplitude

$$\Delta_J = \left(\Delta_{1J}^2 + \Delta_{2J}^2\right)^{-\frac{1}{2}} \tag{12}$$

described by the two-dimensional Gaussian distribution, is greater than a certain chosen value is given by the formula:

$$P(>\Delta_J) = \exp\left(-\frac{1}{2}\left(\frac{\Delta_{1J}^2}{\sigma(\Delta_{1J}^2)} + \frac{\Delta_{2J}^2}{\sigma(\Delta_{2J}^2)}\right)\right). \tag{13}$$

By using the auxiliary variable $J = \Sigma_i \Sigma_j G_{ij} I_i I_j$, where G is the inverse matrix to the covariance matrix of Δ_{ij}, it is possible to write:

$$P(>\Delta_1) = \exp\left(-\frac{1}{2}J\right), \tag{14}$$

where the vector $\mathbf{I}$ is:

$$\mathbf{I} = \begin{pmatrix} \Delta_{11} \\ \Delta_{21} \end{pmatrix}. \tag{15}$$

The probability that the amplitude

$$\Delta = \left(\Delta_{11}^2 + \Delta_{21}^2 + \Delta_{12}^2 + \Delta_{22}^2\right)^{-\frac{1}{2}} \tag{16}$$

described by the four-dimensional Gaussian distribution, is greater than a certain chosen value is given by the formula:

$$P(>\Delta) = \left(1 + \frac{1}{2}J\right)\exp\left(-\frac{1}{2}J\right), \tag{17}$$

where vector $\mathbf{I}$ has the form:

$$\mathbf{I} = \begin{pmatrix} \Delta_{11} \\ \Delta_{21} \\ \Delta_{12} \\ \Delta_{22} \end{pmatrix} \tag{18}$$

In Kolmogorov-Smirnov test, the D_n statistic is calculated,

$$D_n = \sup|F(x) - S(x)| \tag{19}$$

which is the largest absolute difference between the theoretical distribution function $F(x)$ and the empirical distribution function $S(x)$, calculated on the basis of an ordered sample, and then the λ statistics is calculated:

$$\lambda = \sqrt{n}D_n. \tag{20}$$

In the Cramer-von Mises test, the W^2 statistic is computed:

$$W^2 = \sum_{i=1}^{n}\left(F(x_i) - \frac{2i-1}{2n}\right)^2 + \frac{1}{12n} \tag{21}$$

where $F(x_i)$ again is theoretical distribution. In the advanced modification, called Watson test, one uses statistic:

$$U^2 = W^2 - n\left(\bar{F} - \frac{1}{2}\right)^2 \tag{22}$$

where the average value $\bar{F} = \frac{1}{n}\sum_{i=1}^{n} F(x_i)$.

The "theoretical isotropic distributions" simulated as part of the new method for three examples of groups differing in size are presented in Figure 2. During the calculations, various variants of calculating the inclination angle were considered. The consequence of comparing the obtained distributions was the statement of a noticeable deviation caused by the addition of 3° to the inclination angle. The method used in some research works (see Tully 1988) to compensate for the failure to take into account morphological types by adding a 3° may therefore not meet its original assumption.

The results of the analysis of the distributions of δ_D and η angles for the Tully groups, performed using the new research method, are presented in Tables 1 and 2. Since the data from the Tully catalog have been subjected to statistical tests many times, e.g. in Godłowski 2011, Pajowska et. al. 2012, Godłowski and Mrzygłód 2023, it is possible to state that the results obtained using the new method are comparable to those obtained for known morphological types. In the case of both

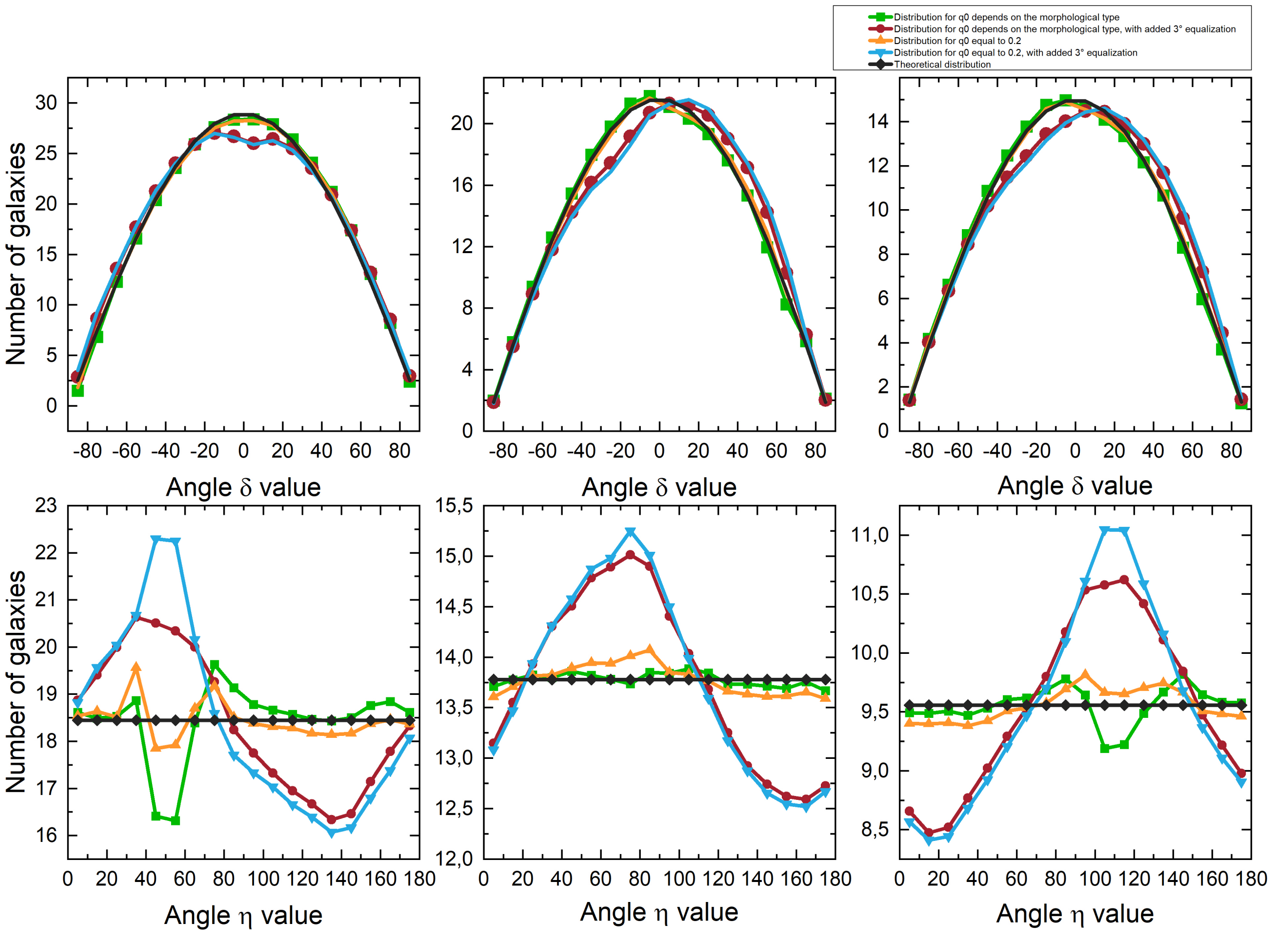

Figure 2: Simulated distributions of the angle δ_D and η for groups 12 (left panels), 21 (center panels) and 52 (right panels)

Table 1: Test for isotropy of the distribution of the angle δ_D of galaxies, obtained using the new method of investigation.

Group	N	χ^2	C	$\frac{\Delta_{11}}{\sigma(\Delta_{11})}$	Δ_1	Δ	$P(\Delta_1)$	$P(\Delta)$	λ	W^2	U^2
11	626	59.24	23.837	-5.127	0.302	0.288	0.0000	0.0000	1.340	0.9076	0.0284
12	332	23.51	0.701	-2.590	0.209	0.195	0.0346	0.1072	0.879	0.2563	-0.2613
13	128	22.40	-2.716	-0.299	0.048	0.174	0.9304	0.8442	0.405	0.0473	-0.1276
14	426	26.87	6.327	-2.483	0.183	0.215	0.0358	0.1166	0.900	0.2252	-0.6374
15	130	9.52	-1.566	-0.042	0.082	0.142	0.7928	0.8999	0.603	0.0975	0.0884
17	80	8.26	-2.106	-0.971	0.183	0.240	0.5284	0.6738	0.722	0.1157	0.1095
21	248	20.46	1.613	-0.759	0.218	0.298	0.0446	0.0695	1.267	0.7711	0.7104
22	126	6.81	-2.527	0.205	0.044	0.053	0.9384	0.9975	0.224	0.0095	-0.1159
23	100	10.41	1.246	0.471	0.073	0.160	0.8812	0.8719	0.438	0.0418	-0.0487
31	210	36.41	19.094	1.667	0.456	0.466	0.0000	0.0001	2.163	2.0593	1.5171
41	192	27.75	11.562	-0.274	0.312	0.392	0.0069	0.0017	1.804	0.9063	-0.6480
42	230	30.49	3.900	-0.431	0.188	0.333	0.1172	0.0522	1.269	0.6391	-0.9776
44	80	23.95	5.304	-0.990	0.316	0.390	0.1277	0.1055	1.213	0.3297	-0.1475
51	228	30.51	7.548	0.933	0.323	0.400	0.0021	0.0013	1.901	1.3166	1.0980
52	172	32.83	9.707	-2.363	0.412	0.399	0.0006	0.0019	1.841	1.0431	1.0122
53	260	21.10	-8.961	-0.429	0.146	0.152	0.2312	0.5331	0.715	0.2149	0.1665
61	258	14.47	1.584	-0.702	0.088	0.198	0.6123	0.3232	0.638	0.1630	-0.5230
64	102	15.93	0.741	0.666	0.227	0.229	0.2564	0.6032	0.904	0.2979	-0.3018

Table 2: Test for isotropy of the distribution of the angle η of galaxies, obtained using the new method of investigation.

Group	N	χ^2	C	$\frac{\Delta_{11}}{\sigma(\Delta_{11})}$	Δ_1	Δ	$P(\Delta_1)$	$P(\Delta)$	λ	W^2	U^2
11	626	51.09	34.516	5.977	0.362	0.364	0.0000	0.0000	2.083	1.4864	1.4824
12	332	38.26	14.673	-0.920	0.361	0.362	0.0000	0.0002	2.096	1.5317	-0.7605
13	128	14.28	-3.196	0.739	0.141	0.279	0.5306	0.2900	0.482	0.0908	-0.0924
14	426	30.46	2.379	1.485	0.206	0.210	0.0113	0.0521	1.801	0.8471	-0.9937
15	130	14.22	-0.256	0.451	0.064	0.198	0.8737	0.6347	0.723	0.1404	0.1404
17	80	34.01	-15.640	-0.414	0.315	0.317	0.1415	0.4103	0.990	0.2576	0.2576
21	248	33.80	3.921	1.321	0.239	0.248	0.0289	0.1073	1.630	0.5451	-0.5519
22	126	18.46	7.166	2.031	0.318	0.405	0.0417	0.0353	1.357	0.4754	0.4349
23	100	27.23	5.659	-1.408	0.473	0.513	0.0041	0.0111	1.571	0.7560	0.6315
31	210	18.66	4.842	1.580	0.202	0.291	0.1164	0.0629	1.289	0.4804	0.4539
41	192	30.01	18.142	3.521	0.451	0.476	0.0001	0.0002	2.036	1.0864	0.9845
42	230	32.96	6.630	-0.174	0.337	0.390	0.0015	0.0015	1.603	1.0393	-0.5294
44	80	19.60	-1.483	0.030	0.273	0.421	0.2254	0.1314	1.120	0.1952	-0.1201
51	228	26.59	-2.132	3.079	0.295	0.298	0.0070	0.0381	1.184	0.3519	0.3292
52	172	42.00	16.865	2.490	0.457	0.514	0.0001	0.0002	2.021	1.4674	1.1505
53	260	11.53	-5.162	0.520	0.047	0.050	0.8673	0.9880	0.266	0.0230	-0.1978
61	258	10.94	2.142	0.849	0.186	0.188	0.1072	0.3355	1.012	0.2731	-0.4037
64	102	52.33	2.005	3.120	0.526	0.683	0.0009	0.0001	2.149	1.5422	1.1508

Table 3: Test for isotropy of the distribution of the angle δ_D obtained using the values of q_0 depending on the morphological type and Fouque and Paturel correction.

Group	N	χ^2	C	$\frac{\Delta_{11}}{\sigma(\Delta_{11})}$	Δ_1	Δ	$P(\Delta_1)$	$P(\Delta)$	λ	W^2	U^2
11	626	29.10	-5.254	-1.302	0.087	0.111	0.3443	0.4907	0.677	0.0710	-0.5891
12	332	12.72	-4.261	-0.935	0.076	0.079	0.6408	0.9215	0.384	0.0455	-0.3625
13	128	27.84	2.881	1.754	0.251	0.438	0.1580	0.0280	0.786	0.2241	0.0307
14	426	19.25	6.103	0.000	0.033	0.219	0.9108	0.0589	0.623	0.1024	-0.7387
15	130	23.10	-7.212	0.799	0.134	0.200	0.5977	0.6819	0.789	0.0932	-0.2091
17	80	5.58	0.524	0.148	0.106	0.244	0.8311	0.7163	0.559	0.0890	0.0890
21	248	19.39	-6.411	0.285	0.084	0.190	0.6978	0.4134	0.889	0.1671	0.1328
22	126	14.82	3.054	0.675	0.120	0.176	0.6707	0.7872	0.707	0.1110	-0.1888
23	100	17.97	-1.012	1.602	0.264	0.318	0.2056	0.3434	0.614	0.1435	-0.0934
31	210	31.90	-0.093	1.240	0.233	0.279	0.0887	0.1243	0.966	0.2677	0.2560
41	192	11.74	5.787	1.044	0.179	0.269	0.2636	0.1864	0.722	0.2679	-0.4889
42	230	17.49	4.119	1.245	0.128	0.279	0.4208	0.0946	0.786	0.1954	-0.4389
44	80	12.06	0.588	-1.046	0.328	0.330	0.1610	0.4258	0.900	0.2598	-0.2228
51	228	17.44	-4.402	0.683	0.092	0.118	0.6561	0.8442	0.552	0.0833	0.0054
52	172	17.94	5.950	-1.504	0.364	0.358	0.0082	0.0450	1.454	0.7803	0.7109
53	260	9.79	-0.320	-0.698	0.077	0.109	0.7056	0.8484	0.523	0.0901	-0.5060
61	258	15.76	0.848	0.780	0.141	0.213	0.3385	0.2690	0.802	0.1902	0.1498
64	102	19.78	-0.098	0.481	0.172	0.226	0.5297	0.6798	0.594	0.0868	-0.1816

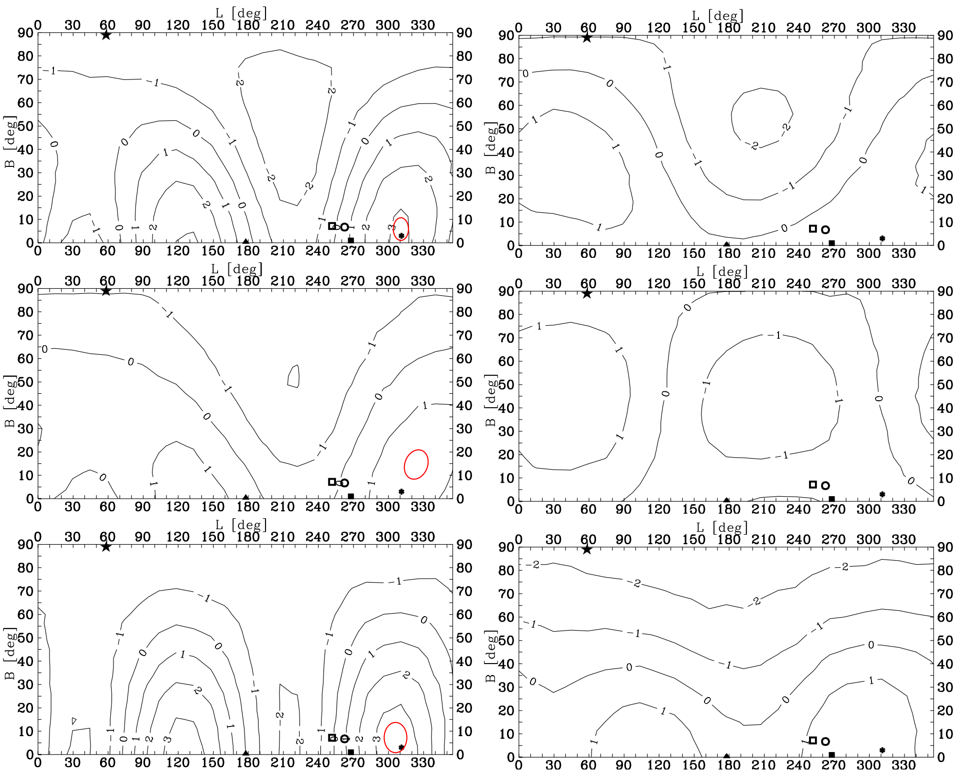

Figure 3: Maps of $s \equiv \Delta_{11}/\sigma(\Delta_{11})$ versus the chosen cluster pole supergalactic co-ordinates $(L,\ B)$ for the cluster 12. In the maps, the results of the Tully data are shown on the left, while results obtained using the values of q_0 depending on the morphological type and Fouque and Paturel correction are given on the right. The maps are presented for ALL cluster galaxies (upper panel), for Spiral (middle panel) and Nonspiral (bottom panel) sub-samples. In the map important directions have been indicated, 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). Red ellipses mark the maxima that correlate with the line of sight.

delta and eta angles, some groups showed that the distribution was non-random. However, the final result of the papers that analyzed the studied groups was that no significant alignment was observed.

The mere consideration of the morphological type does not lead to "fully satisfactory" analysis results, because there is a strong systematic effect in the NBG catalogue data, generated by the process of galactic axis de-projection from its optical image. This effect makes it significantly difficult to find the real alignment during analysis of the spatial orientation of galaxies in clusters, but it can be analyzed in more detail using the methodology described in Godłowski and Ostrowski 1999. For this purpose, for each angle δ_D for each cluster, is computed the Δ_{11} parameter describing the alignment of the axes galactic relative to the selected pole of the cluster, divided by its formal error $\sigma(\Delta_{11})$, denoted as $s \equiv \Delta_{11}/\sigma(\Delta_{11})$. Changing the position of the pole of the coordinate system along the celestial sphere causes the main plane of the system to also change its position. For each such instantaneous coordinate system, we the parameter s is computed. The maps resulted in this way can be analyzed in terms of the correlation of their maxima with important points on the maps. This procedure makes it possible to easily find both preferred and undesirable alignment directions normal to the galaxy planes, if any existed in these clusters. This is because if the rotation axes of galaxies preferred to be aligned in a certain plane, there would be a deficit in the rotation axis in the direction perpendicular to that plane. However, if the orientation of the rotation axes of galaxies favored a particular direction, then there should be a surplus of galaxies with spins pointing in that direction.

Example maps for cluster 12 are presented in Figure 3. In the left panels, obtained for the original NBG Catalog data, strong maxima are observed that correlate with the line of sight. Taking into account the morphological types of galaxies combined with converting q to standard photometric axial ratios according to the formulas of Fouque and Paturel (1985) makes these maxima disappear, as shown in the right panels. The results of the statistical analysis for the data after taking both of these corrections into

Table 4: Test for isotropy of the distribution of the angle η obtained using the values of q_0 depending on the morphological type and Fouque and Paturel correction.

Group	N	χ^2	C	$\frac{\Delta_{11}}{\sigma(\Delta_{11})}$	Δ_1	Δ	$P(\Delta_1)$	$P(\Delta)$	λ	W^2	U^2
11	626	36.84	14.121	3.574	0.213	0.278	0.0009	0.0001	1.101	0.4450	0.0557
12	332	17.37	2.464	-0.595	0.097	0.154	0.4599	0.4165	0.860	0.2365	-0.5615
13	128	17.12	6.297	1.208	0.165	0.382	0.4194	0.0529	1.110	0.2416	0.2405
14	426	14.96	0.338	0.469	0.112	0.144	0.2655	0.3551	0.775	0.1649	-0.5359
15	130	13.72	2.092	0.132	0.115	0.278	0.6530	0.2863	0.643	0.1576	0.1575
17	80	9.10	0.550	-0.135	0.118	0.229	0.7567	0.7188	0.683	0.1061	0.1052
21	248	17.35	-4.710	-0.031	0.064	0.122	0.7749	0.7616	0.564	0.0917	0.0438
22	126	16.57	-2.571	0.172	0.031	0.242	0.9707	0.4506	0.535	0.0286	-0.0656
23	100	10.16	-0.820	-0.856	0.149	0.174	0.5729	0.8232	0.444	0.0477	-0.0294
31	210	17.31	-0.514	1.270	0.147	0.228	0.3238	0.2418	1.104	0.3029	0.3005
41	192	24.38	0.375	2.631	0.289	0.344	0.0181	0.0228	0.962	0.2555	0.1976
42	230	16.05	0.478	-0.083	0.117	0.221	0.4551	0.2283	0.879	0.2468	-0.4326
44	80	14.05	1.000	0.407	0.096	0.393	0.8306	0.1871	0.472	0.0678	0.0524
51	228	28.58	0.158	1.468	0.150	0.249	0.2769	0.1317	1.214	0.4058	0.3993
52	172	17.63	4.651	1.095	0.310	0.314	0.0161	0.0758	1.339	0.6194	0.5459
53	260	14.85	-4.192	0.113	0.121	0.136	0.3857	0.6592	0.675	0.0943	0.0221
61	258	11.86	0.977	1.316	0.133	0.195	0.3174	0.2960	0.955	0.2249	0.2211
64	102	12.71	2.118	1.805	0.274	0.281	0.1482	0.4019	0.627	0.1198	0.0714

account are presented in Tables 3 and 4. The failure to observe any significant alignment for either group indicates that the orientation of the galaxies in the studied Tully groups is random. These results are therefore analogous to those in other research papers regarding this catalog.

4. Conclusions

Data from the Tully Nearby Galaxies Catalog, combined with the results of research analyzing the groups of galaxies used, made it possible to confirm the effectiveness of the new research method. The obtained results indicate that the method may be important in future studies of galaxy clusters. In the case of any astronomical data, the use of the method will involve carrying out an analysis using the designated "theoretical isotropic distributions", which will be previously compared with the "observational" distributions obtained assuming the value of the parameter q_0 equal to 0.2. Since, according to the current view, in the case of catalogs based on automatic galaxy measurements, the Holmberg effect should not be significant, consequently the new method, unlike in the case of the NBG Catalog, can be used without taking into account the photometric correction. Otherwise, however, it will be necessary to first independently estimate this type of correction.

The results of galaxy investigations of orientation are particularly important because they provide information for testing scenarios of the formation of galaxies and their structures. The result obtained in this paper is consistent with the new version of the hierarchical clustering model, which takes into account tidal effects (Catelan & Theuns 1996), as well as with the Li model (Li 1998). According to the current state of knowledge, the ordering of galaxies in clusters increases with their number. For this reason, in small clusters such as Tully's groups, alignment should not be observed - which has been confirmed.

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