

New possibilities for investigation of the orientation of galaxies in clusters

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Attempts to understand the mechanisms driving galaxy and their structures formation contributed to the formulation of various theoretical models describing this issue. Various scenarios make different predictions regarding the orientation of galaxies within large-scale structures, the distribution of their spins directions, and the alignment between the brightest galaxy in the cluster and the major axis of the structure. For this reason, the study of galaxy orientation provides a observational tool for testing models of their formation and remains a cornerstone of extragalactic astronomy and cosmology. The proper study requires consideration of the fact that galaxies are oblate spheroids with the real axis ratios dependent on the morphological type. However, most of the astronomical data available today lacks this type of information. As a result, a new method of investigation based on the estimated frequency of the occurrence of given morphological types of galaxies may prove to be an alternative. The method was applied to galaxies belonging to the clusters of the Local Supercluster using data from Sloan Digital Sky Survey. The obtained results confirm the theoretically predicted lack of significant alignment of the studied galaxies.

Key words: Galaxy clusters: general – fundamental parameters – statistics.

INTRODUCTION

Particular theories of the formation of galaxies and their structures give different predictions about the angular momentum of galaxies, the orientation of galaxies within large-scale structures, the distribution of spins of galaxies, and the alignment between the brightest galaxy and the major axis of its hosting structure [2, 5, 7, 25, 26, 28, 32, 38, 44]. While classical scenarios are still valid in the sense that the new scenarios are essentially modifications of the old ones and they can be classified according to the classical scenarios. Over the years, the original theories have been repeatedly verified and modified many times. The model of hierarchical clustering has remained valid and has been significantly improved.

According to the widely accepted Λ CDM cosmological model, on appropriately large scale, the Universe is considered to be spatially flat, isotropic, and homogeneous, with structures are formed from primordial, adiabatic, self-scaling Gaussian fluctuations [33, 35–37]. This model is currently considered the most probable, although alternative cosmological models are still being considered, and within them, various scenarios of galaxy formation and their structures. It should be noted that the dominant scenarios are those based on the hierarchical clustering model with tidal interactions, which are the only ones that explicitly consider the occurrence of

dark matter. The scientific community’s recognition of these models is also demonstrated by the 2019 Nobel Prize in Physics awarded to Phillip James Edwin Peebles, the scientific father of this class of models, for ‘his theoretical discoveries in physical cosmology’.

A test enabling comparison predicted theoretical results of a given scenario with observations is the investigation of galaxy orientation. This is a consequence of various predictions regarding the distributions of galaxy angular momentum postulated by individual scenarios of the formation and evolution of cosmic structures [22, 23, 34].

The method of alignment analysis first presented by Hawley and Peebles [15] has become the standard tool in this field. It involves a statistical analysis of the distributions of galaxy position angles in order to detect possible deviations from the isotropic distribution, but it is limited only to side-viewed galaxies. An alternative method was proposed by Öpik [29], later applied by Jaaniste and Sarr [20, 21], and further improved by Flin and Godłowski [9, 31]. It allows to include galaxies with all possible settings and positions on the celestial sphere to the study. In addition to the position angles of galaxies, their ellipticities is also used. However, to obtain accurate results, it is necessary to take into account the Holmberg effect in the analysis, which shows that the measured (especially optical) ellipticity of galaxy images

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differs from the true ellipticity of the image [10, 17–19], and that galaxies are flattened spheroids with the actual axis ratio depending on their morphological type.

In past decades, the practice of providing high-quality, readily usable astronomical data in sky surveys such as SDSS [1, 24], DESI [4], Euclid [8], or Kilo-Degree Survey [43] has become increasingly common.

However, these surveys often do not contain information on the morphological types of individual galaxies, and rely on average values of the axial ratio $q_0 = 0.2$, which is used by many researchers, may be insufficient [11, 30]. Alternatively, the estimated frequencies of occurrence of given morphological types can be used [6]. It has been initially shown that methods using these estimated frequencies can produce results comparable in terms of accuracy to those achieved for known morphological types of galaxies [13, 27].

In this paper, using data from the Sloan Digital Sky Survey, we present a practical application of the developed method using estimated morphological types of galaxies. Based on the available literature, the effectiveness of this method was also discussed.

OBSERVATIONAL DATA

The galaxy sample used in the study was taken from the Sloan Digital Sky Survey Data Release 18 [1, 24]. Using the methods of classification galaxy cluster's members described in Tully's papers [39, 40, 42], galaxies located in the Ursa Major region were examined. The sample includes galaxies within the Local Supercluster with redshifts less than 0.01, which were also included in the de Vaucouleurs classification [3]. The classification of Local Supercluster galaxies in terms of the structures they create has been repeatedly verified in papers [41, 42]. The obtained sample of galaxies can be compared in terms of location and completeness with group #13 classified in the Tully's *Nearby Galaxies Catalogue* [41]. As such, it provides a robust sample to verify the effectiveness of the new method for studying galaxy orientation, as well as to indicate potential differences resulting from the choice of this particular sky survey.

METHOD OF ANALYSIS AND RESULTS

The obtained galaxy sample was analysed using the method described in [13, 27], which is an extension of the approach presented in details in [9, 12, 31].

The method calculates two angles determining the spatial orientation of galaxies, as presented in Figure 1. These angles are the ‘polar’ angle δ_D , which is the angle between the normal to the galaxy plane and the main plane of the coordinate system, and the ‘azimuth’ angle η , describing the direction

between the projection of this normal vector onto the main plane and the direction toward the zero initial meridian. In the case of the supergalactic coordinate system, the main plane is the supergalactic equator, and thus, both δ_D and η can be expressed as the relation between the latitude (B) and longitude (L) angles, the angle of the position (P) in the frame of reference, and the inclination angle (i), which is the angle between the normal to the galaxy plane and the observer’s line of sight.

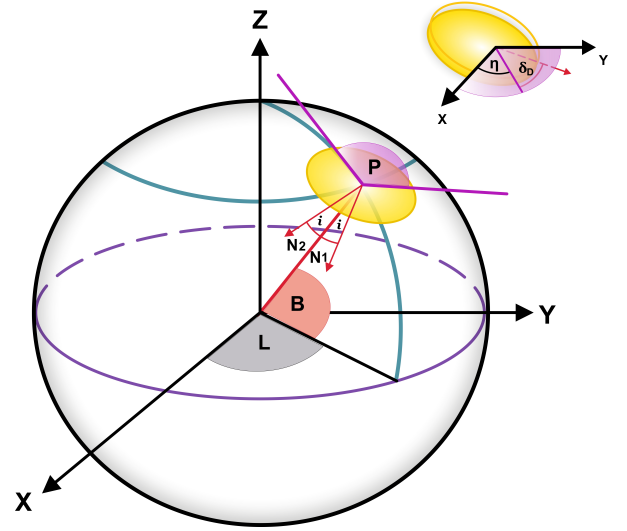


Fig. 1: A schematic illustration of angles δ_D and η .

The deprojection of galaxy images on the celestial sphere gives four solutions for the angular momentum vector. However, since the direction of galaxy rotation is usually unknown, it is sufficient to examine only the directions perpendicular to the galaxy plane. In Figure 1, N_1 and N_2 represent the possible positions of the normal galaxy plane-directed line segment inside the sphere. If the rotation direction of the galaxy were considered, two additional normal vectors N'_1 and N'_2 would appear, which would comprise a directed line segment outside the sphere.

However, only two possible settings of galaxies should be taken into account in the calculations. As a result, the formulas for calculating the angles δ_D and η are expressed as:

$$\sin \delta_D = -\cos i \sin B \pm \sin i \cos r \cos B,$$

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

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

where $r = P - \frac{\pi}{2}$. As a result of the reduction of the analysis into only 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 $S > 0$ should be reversed the sign of δ_D , respectively.

The value of the inclination angle is determined using Holmberg's formula for oblate spheroids [17]:

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

where $q = \frac{d}{D}$ is the ratio of the minor to the major axis diameters, and q_0 is the 'true' axial ratio, which depends on the morphological type of the galaxy [16].

As part of the study, using statistical methods, the obtained real distributions of angles δ_D and η are confronted with its theoretical distributions. To analyze the distribution of these angles, statistical methods described in [13] were used. The analyzed ranges of the angles were divided into $n = 18$, equal to the width of bins.

The χ^2 test is performed using the following statistic:

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

where N is the total number of galaxies in the cluster, N_k and $N_{0,k}$ are the observed and expected numbers of galaxies in the k -th bin, respectively. The expected value of the test statistic is $E(\chi^2) = n - 1 = 17$, with the variance $\sigma(\chi^2) = \sqrt{2(n-1)} = 5.831$. For the assumed confidence level of $\alpha = 0.05$, the critical value of the test is $\chi_{cr}^2 = 27.587$.

The first autocorrelation test determines the correlations between the number of galaxies in neighboring angle bins. The statistic C is defined as:

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

where $N_{n+1} = N_1$. In the case where all $N_{0,k}$ are equal, the expected value of $E(C) = -1$ [12]. The variance of the C statistic is obtained from numerical simulations.

In the Fourier test, the deviation from isotropy is modelled as a slowly varying function of the angle θ , as given by the following relation:

$$N_k = N_{0,k}(1 + \Delta_{11} \cos 2\theta_k + \Delta_{21} \sin 2\theta_k + \Delta_{12} \cos 4\theta_k + \Delta_{22} \sin 4\theta_k + \dots).$$

The Fourier coefficients are calculated using the following formulas:

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

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

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

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

By introducing the auxiliary variable $J = \Sigma_i \Sigma_j G_{ij} I_i I_j$, where G is the inverse matrix of the covariance matrix of Δ_{ij} , the probability values can be expressed as:

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

where

$$\mathbf{I} = (\Delta_{11} \Delta_{21})^T,$$

and

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

where

$$\mathbf{I} = (\Delta_{11} \Delta_{21} \Delta_{12} \Delta_{22})^T.$$

In the Kolmogorov-Smirnov test, the λ statistic is calculated as:

$$\lambda = \sqrt{n} D_n, \text{ where } D_n = \sup |F(x) - S(x)|,$$

with $F(x)$ and $S(x)$ representing the theoretical and empirical distribution functions, respectively. For the assumed confidence level of $\alpha = 0.05$, the critical value of the test is $\lambda_{cr} = 1.358$.

In the Cramer-von Mises test, and its advanced modification, the Watson test, the W^2 and U^2 statistics are computed as:

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

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

where $\bar{F} = \frac{1}{n} \sum_{i=1}^n F(x_i)$ is the average value of $F(x)$. More details on the statistical tests can be found in [12, 13, 31].

Using these statistical tests, the analysis of the δ_D and η angle distributions for the studied sample of galaxies was carried out. The obtained results are presented in Table 1. In order to determine the reliability of the obtained results, they were compared with the results of numerical simulations [12]. Table 2 presents the mean values and standard deviations of the statistical tests for isotropic distributions of δ_D and η angles simulated using our method [13]. Comparison of the results in Table 1 and 2 shows that the distribution is random. The Fourier test further provides an additional possibility to confirm the lack of significant alignment.

The statistical parameter Δ_{11} provided by the Fourier test, describing the preferential orientation of galactic axes with respect to the main axis of the cluster reference frame. For the δ_D angles, negative values of the coefficient Δ_{11} indicate a predominance of galaxies with normals parallel to the main plane of the coordinate system, while positive values of this coefficient indicate a predominance of normals perpendicular to the main plane. 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, the parameter $\frac{\Delta_{11}}{\sigma(\Delta_{11})}$ is computed, where $\sigma(\Delta_{11})$ is formal error of Δ_{11} . This approach, used and described in detail in [14], makes it possible to easily find both preferred and undesirable alignment directions normal to the galaxy planes. The resulting maps can be analyzed in terms of the correlation of their maxima with selected important points.

The maps prepared based on the galaxy sample defined in the previous section are presented in Figures 2. Using the de Vaucouleurs classification [3], the sample was divided into sub-samples of spiral and non-spiral galaxies. Key directions, as seen from the center of the considered cluster, are marked on the maps. The three cluster poles are marked as a black filled star, a square and a triangle. The white circle and inverted triangle indicate the direction to the center of the Local Supercluster and Virgo A cluster center, respectively, while the black pentagon indicates the line of sight from Earth. The positive values of $\frac{\Delta_{11}}{\sigma(\Delta_{11})}$ form ‘hills’ when the direction of the galactic cluster axis is close to the direction of galactic axis alignment, while the negative values creates ‘valleys’ when these directions are perpendicular to each other. For all tested samples, the value of $\frac{\Delta_{11}}{\sigma(\Delta_{11})}$ parameter did not exceed 3.0. The observed ‘hills’ and ‘valleys’ are of the same height in all cases, which is consistent with the lack of significant alignment, confirmed by the results of the remaining statistical tests presented in Table 1. The slight difference observed for the sub-sample of spiral galaxies is a statistically weak, at the 1σ level.

As seen in Fig. 2, the positive extremes in $\frac{\Delta_{11}}{\sigma(\Delta_{11})}$ distributions are located nearby, but they are not strictly correlated with the line of sight direction. This is a significant difference from the situation in [14], when determining the inclinations of galaxies from Tully’s catalogue [41], of an average ‘true’ ellipticity of galaxies $q_0 = 0.2$ when determining galaxy inclinations from Tully’s catalogue [41], of the average ‘true ellipticity’ of galaxies $q_0 = 0.2$ and not taking into account the Fouque and Paturel correction for the Holmberg effect [10, 17–19], see also discussion in [11, 14, 27]. This supports the validity of our method and suggests that the Holmberg effect is not significant for SDSS data.

CONCLUSIONS

Our new method of investigation of the orientation of galaxies in clusters in the absence of information on their morphological types has been tested using new observational data from the Sloan Digital Sky Survey. The group of galaxies located in the Ursa Major (Tully’s group #13) was chosen because for this group we have observational data from the Tully’s catalogue [41], which facilitates the analysis of the results and in particular the investigation of the influence of observational effects.

The results obtained using the developed method of investigation of galaxy orientations is consistent with the predictions from the hierarchical clustering model, which takes into account tidal effects [2], as well as the Li model [26]. Similarly to the studies on small galaxy groups and clusters, e.g. Tully clusters [11, 30], no alignment was observed. The result is therefore consistent with the current state of knowledge, according to which the ordering of galaxies in clusters increases with their number.

REFERENCES

- [1] Almeida A., Anderson S.F., Argudo-Fernández M. et al. 2023, ApJS, 267, 44
- [2] Catelan P. & Theuns T. 1996, MNRAS, 282, 436
- [3] de Vaucouleurs G., de Vaucouleurs A., Corwin H.G. et al. 1991, ‘Third Reference Catalogue of Bright Galaxies’, Springer, New York
- [4] Dey A., Schlegel D. J., Lang D. et al. 2019, AJ, 157, 168
- [5] Doroshkevich A. G. 1973, Astrophys. Lett., 14, 11
- [6] Dressler A. 1980, ApJS, 42, 556
- [7] Efsthathiou G. & Silk J. 1983, Fund. Cosmic Phys., 9, 1
- [8] Euclid Collaboration, Scaramella R. et al. 2022, A&A, A112
- [9] Flin P. & Godłowski W. 1986, MNRAS, 222, 525
- [10] Fouque P. & Paturel G. 1985, A&A, 150, 192
- [11] Godłowski W. 2011, Acta Physica Polonica B, 42, 2323
- [12] Godłowski W. 2012, ApJ, 747, 7
- [13] Godłowski W. & Mrzygłód B. 2023, Appl. Sci., 13, 4845
- [14] Godłowski W. & Ostrowski M. 1999, MNRAS, 303, 50
- [15] Hawley D.I. & Peebles P.J.E., 1975, AJ, 80, 477
- [16] Heidmann J., Heidmann N. & de Vaucouleurs G., 1972, MmRAS, 75, 85
- [17] Holmberg E. 1946, Meddelanden fran Lunds Astronomiska Observatorium Series II, 117, 3
- [18] Holmberg E. 1958, Meddelanden fran Lunds Astronomiska Observatorium Series II, 136, 1
- [19] Holmberg E. 1975, ‘Galaxies and the Universe’, University of Chicago Press, Chicago, USA.
- [20] Jaaniste J., 1977, Calendar of the Tartu Astronomical Observatory, 50.
- [21] Jaaniste J. & Saar E., 1978, IAU Symp., 79, 448
- [22] Joachimi B., Cacciato M., Kitching T.D. et al. 2015, Space Sci. Rev., 193, 1
- [23] Kiessling A., Cacciato M., Joachimi B. et al. 2015, Space Sci. Rev., 193, 67
- [24] Kollmeier J. et al. 2019, Bull. Am. Astron. Soc., 51, 7
- [25] Lee J. & Penn U. 2002, ApJ, 567, L111

Table 1: The results of the statistical tests of isotropy of the distribution of galaxy angles δ_D and η , obtained using the new method of investigation.

Angles	χ^2	C	$P(\Delta_1)$	$P(\Delta)$	Δ_{11}	$\sigma(\Delta_{11})$	$\frac{\Delta_{11}}{\sigma(\Delta_{11})}$	λ	W^2	U^2
δ_D	17.76	5.873	0.8306	0.0626	-0.0802	0.1321	-0.6074	0.570	0.0793	-0.0307
η	25.65	0.998	0.1991	0.0088	0.2180	0.1265	1.7237	0.928	0.2313	-0.1175

Table 2: The mean values and standard deviations of the statistical tests, obtained using numerical simulation.

Angles	χ^2	$\sigma(\chi^2)$	C	$\sigma(C)$	$P(\Delta_1)$	$\sigma(P(\Delta_1))$	$P(\Delta)$	$\sigma(P(\Delta))$	Δ_{11}	$\sigma(\Delta_{11})$
δ_D	17.62	6.97	-0.851	4.627	0.5716	0.2900	0.5597	0.3086	0.0082	0.1533
η	16.65	5.81	-1.055	3.987	0.5108	0.2902	0.5137	0.2896	0.0040	0.0980
			$\frac{\Delta_{11}}{\sigma(\Delta_{11})}$	$\sigma\left(\frac{\Delta_{11}}{\sigma(\Delta_{11})}\right)$	λ	$\sigma(\lambda)$	W^2	$\sigma(W^2)$	U^2	$\sigma(U^2)$
δ_D			0.0636	1.1860	0.648	0.208	0.1252	0.0892	0.0487	0.1291
η			0.0321	0.7841	0.748	0.290	0.1839	0.1832	-0.0250	0.2040

- [26] Li Li-Xin 1998, General Relativity and Gravitation, 30, 497
- [27] Mrzygłód B., Godłowski W. 2023, Odessa Astron. Publ., 36, 20
- [28] Navarro J. F., Abadi M. G. & Steinmetz M. 2004, ApJ, 613, L41
- [29] Öpik E. J. 1970, Irish Astronomical Journal, 9, 211
- [30] Pajowska P., Godłowski W., Panko E. & Flin P. 2012, J. Phys. Studies, 16, 4901
- [31] Pajowska P., Godłowski W., Zhu Z.-H. et al. 2019, Journal of Cosmology and Astroparticle Physics, 2, 5
- [32] Peebles P. J. E. 1969, ApJ, 155, 393
- [33] Peebles P. J. E. & Yu J. T. 1970, ApJ, 162, 815
- [34] Romanowsky A. J. & Fall S. M. 2012, ApJS, 203, 17
- [35] Silk J. 1968, ApJ, 151, 459
- [36] Stephanovich V. A. & Godłowski W. 2015, ApJ, 810, 167
- [37] Sunyaev A. R. & Zeldovich Ya. B. 1970, Astrophys. and Space Science, 7, 3
- [38] Trujillo I., Carretero C. & Patiri S. G. 2006, ApJ, 640, L111
- [39] Tully R. B. 1980, ApJ, 237, 390
- [40] Tully R. B. 1987, ApJ, 321, 280
- [41] Tully R. B. 1988, 'Nearby Galaxies Catalogue', Cambridge University Press, Cambridge
- [42] Tully R. B. 2015, AJ, 149, 171
- [43] Wright A. H., Kuijken K., Hildebrandt H. et al. 2024, A&A, 686, A170
- [44] Zeldovich B. Ya. 1970, A&A, 5, 84

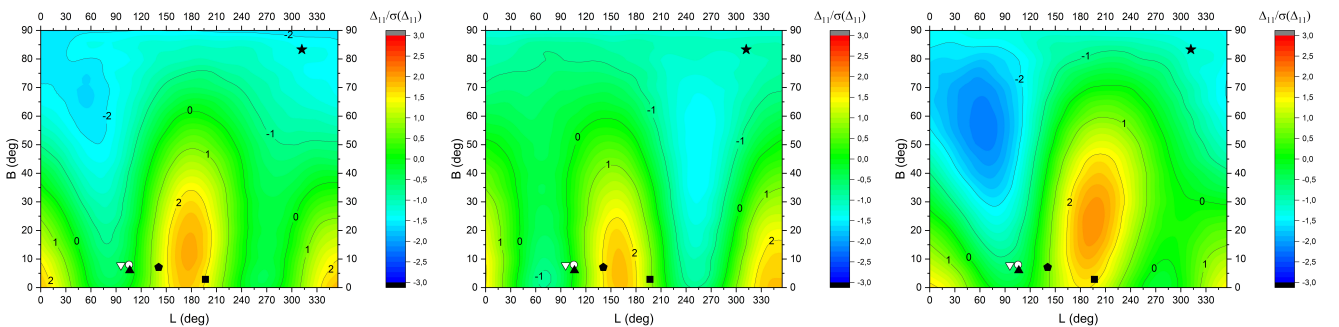


Fig. 2: Maps of $\frac{\Delta_{11}}{\sigma(\Delta_{11})}$ for samples of galaxies studied in this work. The left, centre, and right panels show the entire sample, the spiral and the non-spiral galaxies subsample, respectively. In the maps the important directions are indicated, as seen from the center of the considered cluster. The three cluster poles are marked with a black filled star, a square and a triangle, the white circle and the inverted triangle indicate the direction to the centre of the Local Supercluster and the direction of the Virgo A cluster centre, respectively, while the black pentagon indicates the line of sight from Earth.