Review

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Article

The Alignment of Galaxies in Structures—Review

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Abstract: In this paper the observational result of the alignment of galaxies in different scales is discussed. Especially, the dependence between orientation of galaxies in structures and their size has been analyzed. Both the research methods relevant to the study of this problem and the effects hindering the proper interpretation of the obtained results are discussed. It has been shown that the current state of research indicates that galaxies, their pairs, and compact groups have a non vanishing alignment. In the structures of mass corresponding to groups of galaxies, this feature has not been found, while such phenomenon is observed for more massive structures. These results have been discussed in the light of simulation results and theoretical models of galaxy formation and structure.

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1. Introduction

An important question in modern astronomy and cosmology is the problem of how galaxies and their structures are formed. This topic has been considered by many authors, and as a result, there is a wide variety of works concerning this issue. This work provide a number of theoretical scenarios of these processes.

Currently, the vast majority of cosmologists assume that the Universe evolves according to the ΛCDM model (i.e. cold dark matter with a cosmological constant), in which it is assumed that the Universe is spatially flat, isotropic, homogeneous on a sufficiently large scale [1–3]. It is worth noting, that with the progress of research and the increasing knowledge of astrophysicists and physicists about the Universe, the size of this "sufficiently large scale" of the Universe is subject to modification. At the same time, these studies rule out a significant rotation of the Universe as a whole. This picture is also consistent with the results of numerical simulations [4–10]. In the classical ΛCDM model , structures of various kinds are formed from primordial, adiabatic, self-scaling Gaussian fluctuations. Such a scenario is possible, but it is not unique. An important issue here is the mutual relation between the formation of galaxies and their structures on both small and large scale.

2. Scenarios for Galaxy Formation of Galaxy Theirs Structures

The key issue is to distinguish between different models and scenarios of galaxy formation. A number of classical theoretical models used to develop detailed scenarios for galaxy formation and structures have been proposed [11–18]. The advantage of these classical scenarios is that it is possible to test them observationally due to specific observational predictions are still valid in the sense that the new scenarios are essentially modifications of the old ones and can be classified according to the classic scenarios. Revised and improved creation scenarios have been studied and discussed by numerous researchers [19–35].

2.1. Primary Turbulence Model

In the model of primordial turbulence [36,37], which was subsequently developed by Ozernoy (1978) [38] and Efstathiou and Silk (1983) [18], the angular momentum of galaxies is the artifact of the primordial whirl. The prediction of this model is that the rotation axes of the galaxies are perpendicular to the main plane of the large-scale structure, which is contradictory with the current observational results (see, for example, the review paper Godłowski 2011a [39]) and for this reason it is now mainly of historical significance.

2.2. Hierarchical Clustering Model

The second model is the hierarchical clustering model [11,16,40], which is based on the idea that large-scale structures form in the universe "from the bottom up" as a result of interactions between galaxies. In this scenario, galaxies form first, and as a result of the interaction between them, inhomogeneities in the distribution of galaxies increase and subsequently, larger and larger galaxies are formed. This scenario has had many successes, of which one of the most important is that it correctly predicts the size of galaxy clusters. However, the main difficulty of this model is the need to explain the presence of huge observed structures in the Universe with sizes larger than a few tens of megaparsecs. In the hierarchical clustering model, the source of the angular momentum is the interaction of neighboring galaxies. The original version of this model predicted a random distribution of angular momentum of galaxies. However, it has been quickly noted that in the hierarchical clustering model, the tidal torque mechanism scenario naturally appears [17,41,42] based on the ideas of Hoyle (1951) [43], see review paper by Schaefer (2009) [44]. In this scenario, the main mechanism for galaxy rotation is the tidal interaction of galaxies, and it has been shown that the local tidal shear tensor causes a local alignment of the galaxy rotation axis, which causes the distribution of galaxies' angular momentum to cease to be random [19–22,45,46]. However, there have also been papers questioning this result and arguing that in a hierarchical clustering scenario, distribution of angular momentum should be random [26]. It should be emphasized that one of the main advantages of the hierarchical clustering model is that it is the only model in which the presence of the dark matter is explicitly and naturally included.

2.3. The Li Model

Gamow (1946), Goedel (1949), and then Colins and Hawking (1973) [47–49] considered ideas, that the consequence of the principle of conservation of angular momentum in a rotating universe is that galaxies acquire angular momentum during their formation. At the time, the weakness of this idea was that it predicted the occurrence of the alignment of the angular momentum of galaxies, which was not observed by then. However this occurrence has been confirmed by observations much later (see, for example, Godłowski (2011a) [39]).

In 1998, Li [50] proposed a model in which galaxies form in a rotating Universe. He analyzed a model of a homogeneous universe, in which expansion and rotation occur and the laws of conservation of angular momentum energy hold. Li pointed out that in such a rotating Universe, the consequence of the principle of conservation of angular momentum is the relationship between angular momentum and mass, which takes the familiar form $J\ M^{5}/3$ [51–54]. It should be noted, however, that this relation also occurs in the tidal torque model [42,46,55,56].

Another advantage of the Li model is that, although it originally considers only the dusty component of matter, the dark matter can be easily introduced as a background of colisionless. It should be noted, however, that the Li (1998) model [50], in which galaxies form in a spinning Universe, assumes a global, or at least large-scale, rotation of the Universe. Unfortunately, not only do we not have observational confirmation of the occurrence of such large-scale rotation, but also no good model of the rotation of the Universe based on general relativity has been created, not to mention a model that could be tested, even theoretically, basing on observational data. Moreover, the observed rotation of spiral galaxies cannot be the result of the rotation of the Universe only, because in that case the required rotation of the Universe would be too large in comparison to the anisotropy of relic radiation, for which we have strong observational limitations.

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2.4. Zeldovich Pancake Model

A completely different approach is represented by another scenario, the so-called Zeldovich pancake model [13–15,57,58]. This scenario predicts that structures form "from top to bottom". More precisely, it assumes that the large original structure begins to shrink. Because in real conditions this collapse will almost always be asymmetrical, the result is the formation of a magnetohydrodynamic shock wave. This wave will primarily fragment the structure and at the same time give the galaxies angular momentum. In other words, the mechanism by which galaxies gain momentum is based on the transfer of rotation by a shock wave from the protostructure, resulting in a consistent, non-random orientation of the galactic planes in space. This model predicts a parallel orientation of the axis of galaxies in relation to the main plane of the structure, which is consistent with observational results (see, e.g. [39,59]. The main weakness of the current version of this model is that it describes only the dusty component of matter, and attempts to introduce dark matter into it have been so far unsuccessful. However, even in its current version, this scenario is of great importance because the analyses carried out have shown that in any of the classical models of structure formation, including those based on the concept of hierarchical clustering, a shock wave associated with collapse and fragmentation of the structure/substructure can occur (e.g., [23,29,60–62], which may lead to the alignment of the axis of rotation of galaxies. Of course, the scale of the alignment of the orientation of galaxies varies from model to model, and is usually local rather than global, unlike in Zeldovich's original model. This is illustrated by Bower's scenario [24], where there is no hierarchical clustering at all mass scales, but an anti-hierarchical clustering for small scales appears instead. This is because gravitational tidal effects tend to produce Zeldovich's "pancake" objects [12], rather than structures of the spherically collapsing halo type. However, the main difference between Bower's model and the classical Zeldovich scenario is that the effect is local and occurs on a small scale.

2.5. Summary

The scenario of the formation of galaxies and their structures has been classified into four groups. In fact, there are still attempts to modify the scenarios belonging to all of these groups. However, we preset them, because these classic scenarios are still valid as they are used for classification purposes and the new scenarios are essentially modifications of the old ones. On the other hand, it should be noted that at the moment the prevailing scenarios are based on the model of hierarchical grouping taking into account tidal interactions. The advantage of them is that they are the only ones that explicitly and unproblematically take into account the presence of dark matter.

3. Possibilities of Testing Scenarios of Galaxy Formation and Their Structures

Models of large-scale structure formation in the Universe are closely related to models of galaxy formation and explain different aspects of this process at different scales, as well as predict different observational relationships characterizing these structures. Various scenarios predict different orientations of galaxies in structures, distributions of their angular momentum, as well as other features like the collinearity of the position of the brightest galaxy and the large axis of the structure. Therefore, the study of the orientation of galaxies in space is a standard test for the correctness of galaxy formation scenarios and their structures. In particular, this is because different scenarios for the formation and evolution of cosmic structures give different predictions about the distribution of angular momentum of galaxies [11,14,15,18–22,25,32,46,50,63,64]. If we assume that the normals to the planes of galaxies are their axes of rotation, which is a reasonable assumption at least for spiral galaxies, then this means that different galaxy formation scenarios give different predictions about the orientation of galaxies in space for objects belonging to particular structures - in particular, groups, clusters and superclusters of galaxies. A similar role is played by the study of the orientation of groups and clusters of galaxies in relation to the surrounding matter ("Binggeli effect" - [65], which also provides important information

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about the formation of galaxies and their structures. The ultimate test of the truth of a given scenario is, of course, the consistency of its predictions with observations [66–68].

Studies of the orientation of galactic planes were carried out as early as the 19th century [69]. A review of the methods and results of research carried out before the Second World War is contained in the work of Danver (1942) [70], which is now of only historical importance. Modern research on the orientation of galaxies begins with Holmberg's work in 1946 [71]. He compared the number of galaxies visible from the side and from the front. He discussed the observational effects of optical measurements of galaxy axis sizes and proved that the observed surplus of galaxies visible from the side is an observational effect. In his work, Holmberg discusses the problems that arise in such studies. The issues discussed by Holmberg remain relevant until now. Firstly, he drew attention to the occurrence of the so-called Holmberg effect [71–74], which is caused by the fact that the micrometrically measured values of the major and minor semi-axes of galaxies depend on the ellipticity of the image, which in turn makes it necessary to use the q-axis ratio obtained from micrometer measurements to a standard photometric system. Basing on assumption that galaxies are "flattened spheroids," Holmberg gave a formula for calculating the angle of inclination of a galaxy (to the "plane" of the celestial sphere) based on its observed q-axis ratio. This formula has the form: $cos^2 i = (q^2 - q_0^2)/(1 - q_0^2)$, where i is the angle of inclination, $q = b/a$ is the observed ratio of the axis and q_0 is the "true" ratio of the axis of the galaxy, understood as a triaxial ellipsoid. The difficulty here is that q_0 depends on the morphological type of the galaxy, which is usually unknown. In this case, Tully proposes to take the mean value of $q_0 = 0.2$ [75,76] and this is usual, though not exclusive, approach to this problem [59,77–81].

However, most of the papers of early period, such as Wyatt and Brown (1955) and Brown (1964, 1968) [82–84] were based on the analysis of the position angle distributions of large semi-axes of galaxies in galaxy-rich regions of the sky. Distributions of position angles were also investigated by Reinhardt (1971), Reinhardt and Roberts (1972) [85,86] (in the Reference Catalogue of Bright Galaxies [87]) and Nilson (1974) [88] (in the UGC Nilson catalogue (1973) [89]). They found a very weak preference for alignment of the planes of galaxies parallel to the plane of the equator of the Local Supercluster. Nilson used a luminosity criterion here, i.e. he took into account galaxies brighter than 14.5m. This work is a good illustration of another problem that arises in the study of the orientation of galaxies in structures – the burden of the results with the presence of galaxies that do not belong to the studied structure, i.e. mainly background galaxies, in the analyzed sample. The problem of proper classification of structure members is still relevant, as shown by the recent work by Shi et al. (2023) [90]. Progress in this field was made possible when the catalogues of the radial velocities of galaxies, such as Rood (1980) and Tully (1988) [76,91] were created, because the study of the belonging of galaxies to a particular structure could be based on radial velocities instead of luminosity.

Further important studies of the orientation of galactic planes date back to the work of Hawley and Peebles (1975) [92]. They discussed a method for studying the orientation of galaxies by studying the distribution of position angles in detail. They also studied possible errors and observational effects. In particular, they discussed Brown's earlier results [83,84], pointing out the fact they were insufficiently certain, which was caused by the possibility of observational errors. Hawley and Peebles' method of studying the orientation of galaxies was based on statistical analysis of angle distributions in order to detect possible deviations from the isotropic distribution. These authors proposed the use of three statistical tests to analyze the orientation of galaxies in large-scale structures. Since then, starting with the work of Thompson (1976), [93] this method has become the standard method for studying the alignment of galaxy orientations.

The main tests proposed by Hawley and Peebles are: the χ^2 test, the Fourier test, and the First Autocorrelation test. For each of them the values of position angles were assigned to $n = 36$ angular intervals of equal length. The number of galaxies in the k-th angular interval is the number of galaxies with position angles with values corresponding to that interval. The disadvantage of Hawley and Peebles' (1975) [92] original method was that position angles give good information about the orientation of the galactic plane only for galaxies visible from the side. As a consequence, galaxies

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visible from the front or near the front had to be excluded from the analysis. In addition, if the observer is in the center of the analyzed structure, the galaxies must be close to the plane of the main structure. For example, when considering galaxies belonging to the Local Supercluster (LSC), we should consider only galaxies lying at low supergalactic latitudes B [94].

It has been shown, however, that Hawley's and Peebles' method can be generalized by adding other statistical tests and, also, to cases of angle analysis describing the orientation of galaxies in space. In such a situation, the expected number of galaxies, $N_{0,k}$, even in the case of uniform distribution, does not have to be equal [59,94–98]. A method for determining angles describing the orientation of galaxies in space was proposed by Öpik (1970) [99] and later developed by Jaaniste and Saar (1977, 1978) [100,101]. It is based on the deprojection of images of galaxies. It takes into account not only the position angles of galaxies, but also their ellipticities. As described above, basing on Holmberg's formula, this enables to determine the angles of inclination of galaxies to the direction of view. In this method, there is no obstacle to using of galaxies with all possible alignments and positions on the celestial sphere, including galaxies visible from the front and located far from the plane of the main structure (e.g. Supergaslactics). If we know the positions of galaxies on the celestial sphere (in a given coordinate system), then the orientation of the galaxies in space is described by two angles. The first of these is called the "polar" angle (δ_D). It is the angle between the normal to the plane of the galaxy and the principal plane of the structure (e.g., a supergalaxy). The second angle, called the "azimuth" angle, (η) describes the direction between the projection of the normal onto the principal plane of the structure and the selected direction on that plane (the direction of the X-axis of the coordinate system under consideration). For example, if you analyze galaxies in the Local Supercluster, it could be the direction connecting our galaxy to the center of the Virgo Cluster. However, the original method of Jaaniste and Sarr (1977, 1978) [100,101] contained errors that were corrected by Flin and Godłowski (1986) [95].

Once the "polar" and "azimuth" angles for each galaxy are determined, we can analyze their distributions using statistical methods, such as those proposed by Hawley and Peebles (1975) [92], in order to find possible non-random trends and, in particular, the deviations from the isotropic distribution. Since in the case of the "polar" angle, the theoretical isotropic distribution on the sphere is a cosine distribution, in which not all predicted quantities of galaxies, $N_{0,k}$ are equal, the method of Hawley and Peebls (1975) [92] have to be modified, so that it is suitable for the analysis of angle distributions studied in this method ([94,95,97].

Godłowski (1993, 1994) [94,97] also shows that the idea of Hawley and Peebles can also be applied to the study of deviations from any known distribution, including those not necessarily isotropic. It is also possible to analyze subsamples of galaxies from which we remove some of the objects. Usually objects visible "from the front" are removed, because it is difficult to determine position angles and inclinations for these objects precisely. Moreover, for this class of objects, the problems with the star-galaxy distinction are also the most significant. Godłowski (1993) [97] pointed out that in such a case, the "theoretical isotropic distributions" will deviate from the ideal cosine distribution (for the "polar" angle) or from the uniform distribution (for the azimuth angle) and must be determined by computer simulations. Only such corrected "theoretical isotropic distributions" can be used to study the distributions of observed angles. An example of the use of this procedure is illustrated in the drawings in the paper Flin et al. (2011) [102].

Various variants of the discussed above methods of studying the alignment of galaxies have been used by many authors, with modifications depending on the research problem analyzed [20,25,55,56, 103–111]. In particular, in the work of Aryal and Saurer (2000) [108], a solution to the problem slightly different than in the works of Flin and Godłowski (1986) [95] and Godłowski (1993, 1994) [94,97] is proposed. In the case of "polar" angles, they considered only their absolute values and on this basis, from numerical simulations, they determined theoretical "isotropic" distributions. Then Lee and Pen (2001) [20] described a method for studying the intrinsic alignment of galaxies with respect to the local tidal shear tensor. They discussed in detail both the method for determining the local tidal shear tensor and for study the correlation between both the spins of galaxies and between the spins and the local tidal shear tensor. On the other hand, Brown et al. (2002) [109] discussed a method for studying the intrinsic alignments of the ellipticity of galaxies based on the variance of their ellipticity. Next Noh and Lee (2006a, 2006b) [55,56] investigated the arrangement of the planes visible from the side of spiral galaxies relative to the plane of the local "pancake". This plane was determined locally for each galaxy separately, defining it as the plane passing through the galaxy and its two closest neighbors. Further Trujillo, Carretero and Patri (2006) and Varela et al. (2012) [25,31] defined the normal vector to the local plane of structure as a vector connecting the galaxy with the center of the local "void". Then they studied the distribution of angles between the axis of rotation of the galaxies and the normal vector to the local plane of the structure.

On the other hand, Godłowski et al. (2010) and Godłowski (2012) [98,112] modified the original Hawley and Peebles method, so that it could be used to analyze not only individual structures, but a whole sample of galaxy clusters at the same time. The papers of Panko et al. (2013) and Pajowska et al. (2019) [59,113] show that these improvements to Hawley et al.'s original method can also be extended to studies of the spatial orientation of galaxy planes in clusters, which has significantly expanded the scope of information obtained from such studies.

4. Studying the Orientation of Galaxies at Different Scales

The orientation of galaxies has been studied at different scales. Historically, the first studies were of the Local Supercluster (LSC). The orientation of galaxies in the LSC and its immediate surroundings has been studied in a number of papers. In fact, they began even before de Vaucouleurs' (1953) [114] seminal work on the existence of the Local Supergalaxy, because this region was actually already the subject of work of [71]. Studies made in most of the early work on alignment of the rotation axes of galaxies [82–86,88,101,115–119] showed that galaxies are either oriented randomly or the planes of the galaxies are aligned parallel to the plane of the main structure. These results confirmed either the predictions of the original version of hierarchical clustering theory or the theory of primordial turbulence. At that time, only Jaaniste and Saar (1978) [101], who used not only the position angles of galaxies but also their inclination to the direction of view, claimed that there was a surplus of galaxies in the LSC with their axes of rotation in the plane of the LSC's equator.

The occurrence of discrepancies between the results of early studies on the orientation of galaxies and the reason behind them was discussed in the papers of Flin and Godłowski (1986) and Godłowski (1993, 1994) [94,95,97]. This work showed that the main causes of their occurrence were contamination of the samples by background objects and difficulties in correct interpretation of the results obtained, due to the use of the equatorial coordinate system instead of the Supergalactic system. The importance of choosing the right coordinate system was also pointed out by Flin (1994) [120], Godłowski (1995) [121], Bukhari and Cram (2003) [122], Wu (2006) [107], and especially Aryal, Kandel and Saurer (2006) [123], who showed that the interpretation of the results of studies on the orientation of galaxies in the core of the Shapley Concentration – the cluster Abell 3558 – depends on the coordinate system used. It is also worth noting the results of the work of Kapranidis and Sullivian (1983) [119] who analyzed, in the equatorial coordinate system, the density of the position of the poles of galaxies in regions of size $30^0 x 30^0$ for a sample of spiral galaxies. These authors preliminary thought that they had not obtained a deviation of the polar distributions of the galaxies from the predicted isotropic distribution because they detected a surplus of the poles of the galaxies in only two of the regions analyzed. However, these regions ($\alpha = 195^0$, $\delta = 15^0$ and $\alpha = 15^0$, $\delta = -15^0$) are the direction to the center and anticenter of the Virgo cluster (the center of the Local Supercluster). This means that they have actually detected that the planes of the galaxies prefer an alignment perpendicular to the plane of the Local Supercluster while the normals of these planes are directed at the center of our Supergalaxy.

The results of the work of Flin and Godłowski (1986) and Godłowski (1993, 1994) [94,95,97] showed that the normals to the planes of galaxies belonging to the Local Supercluster are parallelly aligned to the plane of the main structure, i.e. to the equator LSC (and thus the planes of these galaxies are perpendicular to the plane of the equator LSC, and their projections are directed parallel to the direction connecting our Galaxy with the center of the Local Supergalaxy that is, the Virgo Cluster). It was also found that this effect is dependent on the morphological type of galaxies. The results of Flin and Godłowski (1986) and Godłowski (1993, 1994) [94,95,97] were later confirmed by the work of Parnovsky et al. (1994) [124], who found a surplus of the rotation axes of galaxies directed in the direction of $4-6^h$, $20-40^0$. These authors thought that the observed anisotropy was global. They noted that their result was generally consistent with the earlier results of Fliche and Soriau (1990) [125] regarding the orientation of the extended galactic shells of HI and the "cosmic pole" detected in the analysis of distant quasars (5^h30^m, 7^0). However, Flin (1995) [126] analyzed the results obtained by Parnovsky et al. (1994) [124] and indicated that the observed anisotropy in the orientation of galaxies is consistent with the results of the work of Flin and Godłowski (1986) [95] and is not global in nature, but is related to the LSC. The results of the work of Flin and Godłowski (1986) and Godłowski (1993, 1994) [94,95,97] were also confirmed by works of other authors (see, e.g., the review of the results of studies on the orientation of galaxies in LSC Hu et al. 2006) [127].

At first glance, it seemed that the results of studies on the orientation of galaxies in the LSC favored the Zeldovich "pancakes" model, but it can be argued that the situation is more complicated. The first indication that this is indeed the case is the orientation of the galaxies in the substructures of the Local Supercluster. Flin and Godłowski (1990) and Godłowski (1993) [128**?**], while analyzing the orientation of galaxies in LSC substructures defined on the basis of Tully's (1986) [129] work, found that the orientation changes depending on the substructure. In Godłowski's (1994) work [94], it was also found that there is a dependence of orientation on the radial velocities of the galaxies studied. On the other hand, the works of Flin and Godłowski (1989a)[96], Kashikawa and Okamura (1992) [130] and Godłowski (1994) [94] show that the rotation axes of galaxies lying at low supergalactic latitudes are parallel to the main plane of the LSC, and the rotation axes of galaxies lying at high superlatitudes are perpendicular to this plane. In this case, the rotation axes of the galaxies tend to point towards the center of the Virgo Cluster. This result, confirmed by Hu et al. (2006), supports a more complicated hybrid model rather than a simple "pancake" model. Also, the results of the work of Aryal and Saurer (2005a) [131], who found a weak preference for aligning the spins of LSC spiral galaxies in a direction perpendicular to the plane of the supergalactic equator, are not consistent with the predictions of Zeldovich's "pancake" theory. In addition, Aryal and his colleagues analyzed different samples of spiral galaxies in and around the LSC (radial velocities V<5000 km/sec) in a series of papers (Aryal, Kafle and Saurer 2008, Aryal, Neupane and Saurer 2008, Aryal, Paudel and Saurer 2008, Aryal 2010) [132–135]. They found that only barred spiral galaxies exhibit the orientation of the galaxies' planes, with the alignment effect depending on the radial velocities of the galaxies.

Subsequently, it turned out that the results of studies on the orientation of galaxies in the LSC can also be interpreted according to the hierarchical clustering scenario. Early theoretical results on the hierarchical clustering scenario showed that the momentum distribution of galaxies should be random (and this result is still held by some researchers such as Brook et al. 2008 [26]), but later work has shown that a local tidal shear tensor can cause local alignment of the rotation axes [19–22,45,46] also in the hierarchical grouping scenario. The main mechanism for generating galaxy rotation in this scenario is the tidal interaction mechanism, which also causes galaxy orientation alignment to occur.

Initially, it was thought that in the "tidal interactions" scenario, galaxies had angular momentum perpendicular to the main plane of the surrounding structure. However, it turned out that the results of the analysis of observational data indicate the alignment of the angular momentum of galaxies parallel to the main planes of large-scale structures. These results were interpreted as consistent with the tidal interaction scenario (e.g. Navarro, Abadi and Steinmetz (2004), Lee (2004), Trujillo et al. (2006), Lee and Erdogdu (2007), Varela et al. (2012) [22,25,31,136,137]). Therefore, the results of previous studies indicating the existence of galaxy alignment, such as the work of Flin and Godłowski (1986, 1989a) [95,96], have been reinterpreted as consistent with the tidal mechanism (e.g. Navarro,2004,Lee 2004,Trujillo2006,Lee2007,Varela2012). Thus, Lee and his collaborators (Lee and Pen 2002, Lee 2004,

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Lee and Erdogdu 2007, and Lee 2011 [21,136–138]) analyzed the internal alignment of galaxies from observational data, by reconstructing the tidal shear tensor, finding a correlation between the spin directions of spiral galaxies and the axis direction of the tidal shear tensor. Navarro, Abadi and Steinmetz (2004) [22] analyzed a sample of nearby spiral galaxies visible from the side and found that the planes of these galaxies are perpendicular to the main plane of the LSC, i.e. compatible with the results of the work of Flin and Godłowski (1986) and Godłowski (1993, 1994) [94,95,97]. Lee (2004) [136] interpreted these results as consistent with a model of tidal interactions. Based on this scenario, he analytically investigated its implications for the large-scale orientation of galaxies, finding consistency between his predictions and the distribution of orientations of nearby spiral galaxies. Trujillo, Carretero and Patiri (2006) [25] studying the distribution of angles between the rotation axes of galaxies and the vector connecting the galaxy to the center of the local "void" found, that the spins of spiral galaxies located in the vicinity of the local void are perpendicular to the direction of the center of the void, i.e. point in the direction of the shell defined by the matter surrounding the void. In the follow-up work of Varela et al. (2012) [31], the arrangement of galaxies depending on the surrounding matter was also found, but the arrangement was opposite to that from the work of Trujillo, Carretero and Patiri (2006) [25], with the effect depending on the size of the structure studied. On the other hand, Desai and Ryden (2022), studying a sample of galaxies from the SDSS survey, found that the spins of galaxies are aligned according to the distribution of the surrounding matter only for "red" galaxies (i.e. in most elliptical galaxies). It was also noted (e.g. [8,25,31,32,64,67,140], that the direction of the angular momentum with respect to the principal plane of a large-scale structure depends on its mass.

Independently, the results of studies on the orientation of dark matter halos such as Codis et al. (2012) [30] (building on earlier work of of Sugerman et al. 2000,Lee & Pen 2000, Bailin & Steinmetz 2005; Aragon-Calvo et al. 2007; Hahn et al. 2007, Paz, Stasyszyn and Padilla 2008, Zhang et al. 2009 [19,140–145]), Illustris simulations [63,146] or SIMBA [64] also indicate that spin settings will depend on the mass of the structure. Moreover, the work of Trujillo, Carretero and Patiri (2006) and Varela et al. (2012) [25,31] shows relationships between the orientation of dark matter and the orientation of galaxies. The same effect is also indicated by the simulations of Illustris [63,146–148] and EAGLE ([149]. This means that the study of luminous matter provides information about the orientation of dark matter also. This is because in the real Universe, the visible matter of a galaxy is surrounded by a halo of dark matter, which is generally much more stretched and massive than the glowing component of the structure.

It was also noted that the effect found in the work of Trujillo, Carretero and Patiri (2006) and Varela et al. (2012) [25,31] depended on the size of the void and on the position of the galaxy relative to it. More importantly, they showed that the observed trend is consistent with the results of numerical simulations of the alignment of small semi-axes of dark matter halos around cosmic voids, suggesting a relationship between the evolution of the distributions of "visible" matter and dark matter halos.

Noh and Lee (2006a, 2006b) [55,56] analyzed the Tully catalog of nearby galaxies (Tully 2000) [150], and found that the planes of spiral galaxies is aligned and perpendicular to the plane of the local "pancake", which they interpret according to the newly proposed "broken hierarchy" scenario ([24]. In this scenario, we are not dealing with hierarchical grouping at all mass scales. Instead, we have an anti-hierarchical clustering for small scales, which is caused by the fact that gravitational tidal effects produce Zeldovich-type "pancake" objects [12] rather than spherically collapsing halo objects. In contrast to the classic "pancake" scenario, the effect is local and occurs on a small scale.

On the other hand, there were also papers whose authors signaled the existence of a local alignment of the orientation of galaxies. In particular, the work of Lambas, Groth and Peebles (1988) [151] who, while studying the position angles of elliptical galaxies in the UGC catalogue ([89], found that elliptical galaxies are aligned with respect to large-scale structures at a scale of at least $2h^{-1}Mpc$. Muriel and Lambas (1992) [152], taking into account the three-dimensional distribution of galaxies obtained from redshifts, found that spiral galaxies are oriented towards their nearest neighbours, and elliptical galaxies show an alignment at a scale less than $3h^{-1}Mpc$. Cabanela and Aldering (1998)

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[153], while studying the orientation of galaxies in the Perseus Supercluster, drew attention to the fact that the anisotropy they found in the distribution of the orientation of galaxies, may have a local, and not a global (in the sense of orientation in the entire supercluster) character. These results can be interpreted as a outcome of local tidal interactions. Similarly we can interpret the results of Brown et al. (2002) [109], who, while studying the ellipticity of galaxies from the SuperCosmos survey (mean redshift z=0.1), found that they are correlated on a scale between 1 and 100 arcminutes ("arcmin"). The significance of the latter is unclear, although the authors interpret it as a local effect, consistent with tidal interaction theory.

Large-scale studies of alignment the angular momentum of galaxies were also undertaken. Thus, Paz, Stasyszyn and Padilla (2008) [140] analyzed galaxies from the Sloan Digital Sky Survey. They found that the angular momentum of galaxies is perpendicular to the planes of large-scale structures, but this effect applies only to massive structures. In contrast, in the case of low-mass structures, the authors did not observe this effect. Paz, Stasyszyn and Padilla (2008) [140] interpreted these results as consistent with their simulations which were taking into account the tidal interaction mechanism. Jones, van der Waygaert, and Aragon-Calvo (2010) [154] found that the spins of spiral galaxies on the cosmic web tend to align along the large filament axis, which they interpret as a "fossil" record of the effect of long-range tidal interactions.

Samuroff et al. (2023) [155] analyzed galaxy intrinsic alignments using the Dark Energy Survey Year 3 and found the occurrence of the intrinsic alignment effect on a scale of $6 < r < 70 Mpc/h$. The results of the work of Tovmassian (2021) [156] on the occurrence of galaxy alignment in clusters can also be explained by the occurrence of large-scale alignment. Shamir (2023) [157], on the other hand, believes that virtually all of the data used to study the orientation of galaxy spins agree with the claim that galaxies observed from Earth have a preferred spin direction and an observed distribution of galaxy spin directions from the Earth form a dipole axis on the cosmological scale, where one (although not the only) of the possible interpretations of this is the occurrence of anisotropy on the cosmological scale.

The largest scale of alignment was found in a series of works by Hutsemekers [158–160] where they analyzed the alignment of quasar polarization vectors. In the paper by Hutsemekers et al. (2005) [160], based on a new sample of 355 quasars with significant optical polarization, they found that the polarization vectors of quasars are not oriented randomly on the celestial sphere. The polarization vectors show an alignment on a scale of about 1 Gpc, and it has been found that the mean polarization angle rotates with a redshift of about 30^o per Gpc. The first possibility is that there is a global (or at least very large-scale) rotation of the Universe, which could potentially explain this effect. However, the observations can also be explained in other ways, such as the effect of oscillations of pseudoscalar photons. The results of the work on quasar polarization vectors discussed above are generally not disputed (with the exception of the work of Joshi et al. (2007) [161], where no effects were found when analyzing a Jackson et al. (2007) sample of quasars [162], but the nature of the origin of the observed effect is still debated. Possible explanations for discussed above the observed alignment effect have been discussed in details by Hutsemekers (1998), Hutsemekers and Lamye (2001), Hutsemekers et al. (2005) [158–160] and have quickly become the focus of interest of many authors [163–170]. Tiwari, Prabha, and Jain (2022) [171] draw attention to the role of the intergalactic magnetic field here. The cosmological origin of the arrangement of the orientation of quasar spins is indicated in the works of Slagter and Miedema (2021) and Slagter (2022) [172,173]. The problem of the occurrence of cosmological anisotropy and its implications are discussed in detail in Migkas et al. (2021) [174]

It was also pointed out that the study of galaxy orientation is important for the study of weak gravitational lensing. Heavens, Refregier, and Heymans (2000) [175] stated that the intrinsic alignment of spins in pairs of galaxies must be taken into account when studying weak gravitational lensing, as otherwise it would act as a systematic effect (see also Soussana et al. (2020) [176] for modern simulations). Crittenden et al. (2001) [177] have already shown that, at least in the tidal interaction scenario, it is possible to distinguish spin alignment effects from weak gravitational lensing effects.

On the other hand, Heymans et al. (2004) [178] confirmed the occurrence of spin alignment in pairs of galaxies and analyzed in detail the method of determining and removing them when conducting studies on weak gravitational lensing. Systematic effects in the study of weak gravitational lensing, related to the alignment of galaxy orientations, have also been discussed in the papers of Mandelbaum et al. (2005) and Troxel & Ishak (2014, 2015) [179–181].

The above review of galaxy orientation studies indicates that there is no clear evidence toward any of the galaxy formation scenarios. There are also no grounds for explicitly ruling out any of the scenarios, with the possible exception of primary turbulence scenarios. Much of the discussed results can be interpreted either in favor of the "pancakes" scenario or in favor of the tidal interactions scenario. It is therefore necessary to test the orientation of galaxies in galaxy structures more closely to see if we can get additional arguments in favor of one of the scenarios. One of such approaches that may provide additional arguments in favor of one of the scenarios is to study the orientation of galaxies in clusters

5. Studying the Orientation of Galaxies in Structures

Studying the orientation of galaxies in groups and clusters of galaxies is an issue that sheds light on galaxy formation scenarios. This problem has been studied both on theoretical grounds, e.g.. [182,183] and, above all, observationally. These studies also have a long history, and at first glance do not give unambiguous and easy-to-interpret results, even as to the mere presence of orientation alignment. The first group of papers consists of results indicating the existence of such an alignment. Already in the study of Thompson (1976) [93] the occurrence of an alignment in the orientations of galaxies in the Virgo Cluster and A2197 was found. Helou and Salpeter (1982) [184] analyzed 20 galaxies in the Virgo Cluster and found that their spins were not randomly distributed, although the nature of such a non-random distribution was unclear. Mac Gillivray and Dodd (1985a) [117] investigated the orientation distribution of galaxies in the Virgo Cluster and showed that the planes of galaxies in the cluster are oriented perpendicularly to the "direction to the center of the cluster". This means that the rotation axes of the galaxies are directed towards the center of the cluster. This result is consistent with later results for the entire Local Supercluster [94,95,97,127]. Adams (1980) [185] discovered a bimodal distribution of galaxy orientations by analyzing combined data from seven galaxy clusters (A76, A179, A194, A195, A999, A1016, A2197). The bimodal nature of the distribution was that the large semi-axes of the galaxies tended to align either in the direction of the large semi-axes of the clusters or in the direction perpendicular to it, avoiding intermediate alignments. A similar result was obtained by Gregory, Tompson and Tift (1981) [186], who found in the supercluster Perseus (A426, A262) and in groups around galaxies NGC383 and NGC507, a bimodal distribution of position angles of galaxies with two maxima. The position of one of them corresponds to the position angle of the Perseus supercluster. This means that in this case we have two populations of galaxies with almost perpendicularly oriented axes. Interestingly, in high-abundant structures such as A754 [187], A14 [188], A1656 [189–191], a non-random alignment of the galaxy rotation axis has been found. A more complicated picture was shown by the analysis of the alignment of galaxies in the Coma cluster by Adami et al. 2009 [192]. They found that the alignment of galaxies occurs only in a subset of cluster regions, with galaxies of early and late spectral types being oriented differently. Similarly, the preferred direction of orientation i n different regions of the cluster differs between themselves. The alignment of the planes of the galaxies was found in cluster 1689, the most distant cluster in which the alignment effect was sought at the time [193]. If we move on to the study of the alignment of galaxies on a larger scale, then the scale corresponding to superclusters has found a non-random orientation of galaxies not only in the Local Supercluster, but also in other superclusters [106,120,153,186,189,194–198].

However, other researchers have not found any significant alignment of galaxy orientation. Kindl (1987), Bukhari (1998), as well as Bukhari and Cram (2003) [103,122,199] did not find any alignment when studying the orientation of galaxies in clusters. Han, Gould, and Sackett (1995) [200] studied a region of the Local Supercluster with a higher density of galaxies. By analyzing a sample of 60 galaxies

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with precisely determined spins, they found no alignment. Hoffman et al. (1989) [201] also found no alignment when examining the orientation of a sample of 85 galaxies in the Virgo cluster with precisely determined spins.

A slightly different result was obtained by Flin and Olowin (1991), Trevese, Cirimele and Flin (1992), Kim (2001) [202–204], who, while studying isolated Abell clusters, found that in these clusters only the brightest galaxies show signs of alignment. A similar result was obtained by Torlina, De Propris and West (2007) [205] while they studied the Coma cluster and its surroundings. A correlation between the orientation of the brightest galaxy in the cluster and the large axis of the cluster was investigated many times and was founded by Sastry (1968), Carter and Metcalfe (1980), Binggeli (1982), Struble and Peebles (1985), Rhee and Katgert (1987), West (1989b, 1994), van Kampen and Rhee (1990), Plionis (1994), Fuller et al. (1999), and Kim et al. (2002) [65,206–215]. Gonzalez and Teodoro (2010) [216] state that the occurrencethe occurrence of the alignment of only the brightest galaxies in the cluster is an the effect of gravitational tidal forces. Yuan and Wen (2022) [217], studying the correlations between the alignments of the brightest galaxies in the cluster and the parent cluster, confirmed the existence of this effect, while noting that this effect is even stronger if we take not the optical structure, but X-ray clusters.

On the other hand, Godłowski and Ostrowski (1999) [218] analyzed, in various coordinate systems, the orientation of galaxies in 18 Tully groups. These groups, selected from Tully's (1988) catalogue [76], are part of the Local Supercluster. The second supergalactic coordinate system was adopted as the base coordinate system (Flin and Godłowski 1986) [95]. The position of the pole of the coordinate system was then changed (in increments of 5^0), both in supergalactic latitude B and longitude L. This procedure makes it easy to find both the preferred and anti-preferred orientations of the normals to the planes of the galaxies, if such were present in those clusters. This is because if the rotation axes of galaxies preferred to be aligned in a certain plane, there would be a deficit of the rotation axis in a direction perpendicular to that plane. If, on the other hand, the alignment of the axis of rotation of the galaxies favors a particular direction, then we should get a surplus of galaxies with spins directed in that direction. As a result of the analysis, a strong correlation was observed between these maxima and the direction of view of the cluster. However, no such correlations were detected in the case of the other analyzed directions. The resulting surplus of the rotation axes of galaxies directed towards the line of sight of the cluster suggests that we are rather dealing with a systematic effect related to the process of deprojection of galaxies' axes from their optical images.

The main result of Godłowski and Ostrowski's (1999) [218] work is therefore a detection of a strong effect (called the "line of sight" LOS effect) in the catalogue data, associated with the process of deprojection of galaxies axes from their optical images. It has been shown that the process of deprojection of galaxies based on catalogue data generates significant systematic errors that must be taken into account in the study of galaxy orientation. The effect largely masks a possible weak effect of alignment the orientation of the galaxies in the clusters analyzed. The problem with the deprojection of optical images has already been signaled by other authors, most notably Kapranidis and Sulivian (1983) [119] and Cabanela and Aldering (1998) [153]. In (Godłowski and Ostrowski 1999) [218] paper it has been proven that this effect is important for Tulle's catalogue (1988) [76]. The main reason for this is the fact that Tully, when calculating the angles of inclination of galaxies, assumed that the "true" ratio of the axes of galaxies is $q_0 = 0.2$. This is a very bad approximation, especially for non-spiral galaxies (Godłowski 2011b, Pajowska et al. 2012) [219,220]. This work also shows that if instead of taking the values of the angles of inclination given in the Tully catalogue (1988), one calculates the angle of inclination from Holmberg's formula: $\cos^2 i = (q^2 - q_0^2)/(1 - q_0^2)$, taking the values of q_0 for galaxies of different morphological types from the work Heidmann, Heidmann, de Vaucouleurs (1972) [221], it turns out that the surplus of galaxies with normals to their planes directed towards the line of sight, obtained by Godłowski and Ostrowski (1999) [218] disappears. Godłowski and Mrzygłód (2023) [218] confirmed this result, while showing that if we do not know the morphological types of galaxies, it is better to randomize the morphological type of the galaxy according to the known

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frequency of their occurrence in the cluster (for example, according to Dressler (1980) [77])) and use this morphological type to determine the angle of inclination from the Holmberg formula, rather than to assume an approximation $q_0 = 0.2$. As a result, we confirmed that there is no alignment of the rotation axes of the galaxies in the analyzed Tulle groups. It should be emphasized that when modeling the LOS effect for a sample of galaxies from the UGC catalogs [89] and ESO [222] taking into account the effects of the true ratio of the galaxies q_0 (depending on the morphological type according to the recipe of Heidmann, Heidmann and de Vaucouleurs (1971)) [221] and the Holmberg effect (according to the recipe of Fouque and Paturel (1985) [74] it has been found that for UGC/ESO catalogues the LOS effect, if any, is much smaller [219]. These results are consistent with that of Bahcall, Guhathakurt, and Schneider (1990) [223], who found that there is no surplus of front-facing elliptical galaxies in the UGC. Instead, they found a surplus of spiral galaxies visible from the side, which can be explained by both the Holmberg effect and the "falling out" of faint spiral galaxies classified as stars.

The problem of the "true" shape of galaxies is also very relevant in the context of the Tully-Fisher relationship (Tully and Fisher 1977) [75] and the Baroness Tully-Fisher relationship ([224,225] and the review by Gurovich et al. (2010) [226]. One of the significant problems in this relationship is to correct the position of the galaxy to an "edge-on" position. The angle of inclination is obtained assuming a "true ellipticity" of $q_0 = 0.2$, which, as we have shown, is not a good approximation. Tully Fisher's relation is the place where observations and the theory of determining the angular momentum of galaxies meet.

The orientation of galaxies in Tully groups was re-analyzed in Godłowski, Szydłowski and Flin (2005) [227]. Analyzing the distribution of position angles in the supergalactic coordinate system, no anisotropy was found in the distribution of the angles studied. Also, Aryal and Saurer (2005c) [228], analyzing three richness class zero Abella clusters, S0794, S0797 and S0805, found that the orientation of galaxies in these poor clusters is random.

Godłowski, Baier, and MacGillivraya (1998) [187] analyzed the orientation of galaxies in the Abell 754 cluster. Both the distributions of the position angles of the galaxies and the distributions of the "polar" and "azimuth" angles were analyzed. The cluster Abell 14 was also studied using the same method by Baier, Godłowski and MacGillivray [188]. They confirmed the presence of the LOS effect which was detected by Godłowski and Ostrowski (1999) [218] and which is causing the process of deprojection of galaxies based on catalogue data to generate significant systematic errors.

Since the effect has been confirmed on the basis of independent observational data (in this case from the COSMOS/UKST Southern Sky Objects Catalogue [229], this means that it occurs not only for data from the Tully Catalogue (1988) [76]. Thus, it may have had the effect of falsifying some of the earlier results on the orientation of galaxies. The main reason for this effect in the COSMOS/UKST Southern Sky Objects Catalogue [229] seems to be that, due to the lack of information about the morphological types of galaxies. Because of this it has been assumed that the "true" ratio of the axis of the q_0 galaxies is 0.2 for all galaxies, which is, as previously mentioned, a very bad approximation, especially for non-spiral galaxies. It should be noted, however, that the effect found in the works of Godłowski, Baier and MacGillivray (1998) [187] and Baier, Godłowski and MacGillivray (2003) [188] is much stronger than that found for Tully's groups in the work of Godłowski and Ostrowski (1999) [218]. The possible reason for this may be that COSMOS has trouble distinguishing between a star and a galaxy [122]. As a result, the analyzed sample may be contaminated by stars incorrectly classified by COSMOS as galaxies. This emphasizes the importance of proper identification of catalogue objects as galaxies. It should also be mentioned that Cabanela and Aldering (1998) [153] have shown that an effect analogous to the Holmberg effect is also present when the data come from a catalogue in which the sizes of galaxies were measured by digital scanning. Using the Minnesota Automape Plane Scaner [230], they constructed a catalog of galaxies belonging to the Fish-Perseus supercluster. Bas on Huizinga's (1994) [231] analysis, they pointed out that the outer regions of spiral galaxies (as opposed to their inner regions) are optically thin and, as a result, the measured sizes of galaxies should increase with their inclination, which in turn leads to overrepresentation of such galaxies in their catalog.

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Although the analysis of Cabanela and Aldering (1998) [153] should be approached with some caution due to a number of inaccuracies in their work, it clearly shows that the effect they found must be taken into account during studies of the orientation of galaxies using their ellipticity also in the case when we take data from catalogs in which the sizes of galaxies were measured by digital scanning.

On the other hand, an independent analysis of the position angle distributions of galaxies belonging to the clusters Abell 754 and Abell 14 showed that the distribution of orientations of galaxies in the double cluster Abell 754 is non-random, with the planes of the galaxies perpendicular to the plane of the main cluster [187]. In the cluster Abell 14 , also a non-random distribution of the orientation of the galaxies was found, however, the direction of the found alignment (relative to the plane of the main cluster) is perpendicular to that found in the cluster Abell 754 [188]. According to di Fazio and Flin (1988) [232], such a discrepancy in the directions of the preferred orientations of galaxies relative to the plane of the main cluster may be related to the presence of two types of galaxy clusters: flattened ("oblate") and elongated ("prolate"). Another explanation for the observed discrepancies is possible on the basis of the tidal interaction scenario. In the papers discussed in the previous chapter by Paz, Stasyszyn and Padilla (2008), Trujillo, Carretero and Patiri 2006, Varela et al. 2012) [25,31,140], it was noted that the direction of the angular momentum of individual members of the structure relative to the principal plane of a large-scale structure depends on its mass, and there are also relationships between the orientation of dark matter and the orientation of galaxies. This is important because, as already mentioned, the results of work on the orientation of dark matter halos [30], or Illustris simulations [63,146] predict the occurrence of such effects.

The question that naturally arises is whether the orientation of galaxies depends on the mass of the structure being studied. This problem has been qualitatively investigated by Godłowski, Szydłowski and Flin (2005) [227] and Aryal, Pudel and Saurer (2007) [233]. With the appearance of new observational data, it has also become possible to study this issue in a quantitative way. Godłowski et al. (2010) [98] analyzed the orientation of galaxies in 247 Abell clusters. The analysis was carried out on a sample of 247 clusters with at least 100 objects from the PF catalogue (Panko and Flin 2006) [234] and identified in the ACO catalogue [235]. For each cluster analyzed in the work of Godłowski et al. (2010) [98], both the distributions of position angles and "polar" and "azimuth" angles in both the equatorial and supergalactic systems were determined. Statistics from the χ^2 test and the Fourier test [92,94,95,97] were used to analyze the distributions of these angles. By the linear regression method it was examined whether the values of the analyzed statistics increase with the increase in the size of the cluster, which would indicate an increase in the alignment of the orientation of galaxies with the size of the cluster. Independently, the same method was used to investigate the relationship between the arrangement of the orientation of galaxies and their morphological type according to the Bautz-Morgan classification (BM) and the dispersion of the velocity of galaxies in clusters. In particular, in the work of Godłowski et al. (2010) [98] it was found, contrary to the suggestion of Aryal and Saurer (2004, 2005b, 2005c, 2006), Aryal, Pudel and Saurer (2007) [123,228,233,236,237] that the alignment of the orientation of galaxies is weakly correlated with their morphological type according to the Bautz-Morgan classification (BM). The correlation suggested by Plionis et al. (2003) [238] between the degree of alignment of galaxy orientation and the dispersion of galaxies in clusters has also not been confirmed. However, the most important result of the work of Godłowski et al. (2010) [98] is that they found that there is an increase in the alignment of the orientation of galaxies with the size of the cluster. The question that arises is whether in such a sample of rich Abell clusters it is possible to determine the existence of the alignment of galaxies as such, and not just increase of alignment with the richness of the structure. This problem was addressed in Godłowski (2012) [112], where a larger sample of galaxies were considered.

Previous works on cluster orientation have focused on one or at most a few galaxy clusters. The largest number of objects was studied by Aryal, Pudel and Saurer (2007) [233] in a paper summarizing a series of their papers on the orientation of galaxies in clusters. Godłowski (2012) [112] considered a sample of 247 Abell clusters. This is an order of magnitude more than that of Aryal, Pudel, and Saurer (2007) [233]. As a result, it was possible to effectively test the statistical properties of the entire sample.

In the work of Godłowski (2012), [112] for each of the studied clusters, the values of test statistics measuring the deviation of position angle distributions from the uniform distribution were calculated. Then, average values of the test statistics and their errors were calculated. These values could now be compared with both theoretical predictions and the results of computer simulations. The results showed that the orientation of the galaxies in the studied clusters is non-random, i.e. the occurrence of an alignment of orientation of galaxies was found in the analyzed sample of 247 rich Abell clusters. This result was confirmed in the work of Pajowska et al. (2019) [59], where additional tests dedicated to the study of distributions on the sphere were used, such as the Cramer-von Mises test or the Watson test.

If we try to systematize these observational results, first of all, it should be stated that among the models of galaxy formation, the dependence of angular momentum of structures on their mass is predicted only by the hierarchical grouping model [42,46,55,56,239] and Li model [50,227,240]. The hierarchical clustering model simply predicts an increase in angular momentum of structures with mass according to the formula $J\ M^{5/3}$ (although the $J\ M^{4/3}$ relationship is also possible [239,241], while the Li model shows that this relationship can be more complicated and, additionally, that groups and poor galaxy clusters are structures with minimal angular momentum citeGodlowski2003a,Godlowski2005.

In the previously discussed work (Godłowski, Szydłowski and Flin 2005) {citegodlowski2005, the relationship between angular momentum and the mass of the structure resulting from observational data was also analyzed. They investigated how this picture is drawn in relation to the masses of structures composed of galaxies, starting with the smallest structures, i.e. pairs of galaxies. Studies of pairs of galaxies have shown that their angular momentum comes mainly from the orbital motion of galaxies [243**?** ,244]. Helou (1984) [245] analyzed a sample of 31 pairs of galaxies and found an "anti-order" in the spins of these galaxies. Parnovsky, Kudrya, and Karachentsev (1997) [**?**] found a weak alignment in physical pairs of galaxies. Alignment in pairs of spiral galaxies was also detected by Pestana and Cabrera (2004) [246]. The existence of internal spin alignment in pairs of galaxies has been independently confirmed by Heymans et al. (2004) [178] in their study of weak gravitational lensing, where it was necessary to estimate and remove the effects associated with the alignment of galaxy orientations. Also, the analysis of the distribution of the satellites of the Milky Way shows their non-random distribution (they are arranged perpendicularly to the disk of the Milky Way), which indicates the alignment of their orbits [182,183]. In compact groups, galaxies rotate in elongated orbits around the center of the group (Tovmassian et al. 2001 [247]), which contributes to the total angular momentum of the system. The alignment of orientation in pairs of galaxies has also been confirmed theoretically [248]. Thus, it can be concluded that structures such as galaxies and their satellites, pairs of galaxies and compact groups of galaxies, have a total non-zero angular momentum.

Structures with higher masses are groups and clusters of galaxies. For groups and clusters of galaxies, we do not have evidence that these objects rotate [249–252]. Furthermore, Hwang & Lee (2007) [251] investigated the dispersions and velocity gradients of 899 Abell clusters, finding that only 6 of them exhibit possible rotation. The hypothetical non-zero angular momentum of galaxy groups and clusters would therefore come mainly from the hypothetical alignment of galaxy spins [253]. We do not have sufficient evidence of the occurrence of an alignment of the rotation axis of galaxies in groups and poor clusters of galaxies. Moreover, it is clear that in isolated Abell groups, only the brightest galaxies show signs of alignment [202–204]. On the other hand, in clusters with large numbers, such as A754 [187], A14 [188], A1656 [189–191], a non-random alignment of the axis of rotation of galaxies has been found. An analysis of the alignment of galaxies in the Coma cluster was carried out by Adami et al. (2009) [192]. They found that the alignment of galaxies appears only in subsections of the cluster, with galaxies of early and late spectral types being oriented differently. Similarly, the preferred orientation in different regions of the cluster differs from one another. The alignment of the planes of the galaxies was found in cluster 1689 [193]. This result is noteworthy because it is the most distant individual cluster in which the alignment effect has been analyzed so far. The occurrence of non-random orientation of galaxy spins has been found both in the Local

Supercluster and in other superclusters. This effect has been found in the superclusters Hercules [120], Coma/A 1367 [106,189,196,198], and Perseus [153,186,194,195,197]. One of the few exceptions is the work of Malla, Saurer, Aryal (2022) [254] where no galaxy alignment was found in SDSS Supercluster S[184+003+0077].

The previously discussed hypothesis from the work of Godłowski, Szydłowski and Flin (2005) [227] was discussed in detail in the review paper, [39], where numerous arguments in support of it were presented. The picture outlined in the work of Godłowski, Szydłowski and Flin (2005) [227] was confirmed in subsequent papers dealing with the problem of galaxy orientation. For example, Yang et al. (2006) [255] found, and Sales and Lambas (2009) [256] and Wang et al. (2009, 2010) [257,258] confirmed, that the satellites of the central "red" galaxies are aligned along their large axes. The arrangement of the central satellites of galaxies has recently been confirmed also in the work of Wang et al. (2019) [259] in the case of the Local Group of Galaxies and the work of Wang et al. (2020) [260] in the case of the sample SDSSDR12

In a series of papers Aryal and his colaborators [123,228,233,236,237] dealt with the orientation of galaxies in 32 clusters of different sizes. They confirmed in [233] a picture in which we do not detect the orientation alignment of galaxies in small clusters, but such an alignment is observed in a number of rich galaxy clusters.

It should be noted, however, that this simple picture may be distorted by significant influence on the formation and alignment of angular momentum of galaxies of the conditions under which individual structures formed ("environmental effects"). In the paper by Godłowski et al. (2011) [39], the orientation of galaxies in rich Abell clusters was again analyzed, but this time taking into account their belonging or not to superclusters. It turned out that there was a statistically significant difference between the two cases. In contrast to the sample of 247 clusters, where the alignment increased with the size of the cluster, for the clusters belonging to the superclusters we do not observe this effect. In addition, it has been noted that the alignment decreases with the size of the supercluster, but still the orientations of galaxies in clusters belonging to superclusters (analyzed by the Godłowski (2012) method [112]) are non-random. The fact that the orientation of galaxies is observed to depend on both the position of the clusters and the abundance of superclusters indicates a significant influence of environmental effects on the orientation of galaxies. Independently, Huang et al. (2016, 2018) and Wang et al. (2018) [261–263] indicate possible role of environmental effects on central galaxy and radial alignments, contrary to the opinion of Sifon et al. (2015) [264] who did not find radial alignment for a sample of galaxies belonging to clusters. Moreover, Huang et al. (2016, 2018) and Hwang (2018) [261,262,265] noticed the role of central dominant galaxies in structures (like galaxy clusters) and merger process events which tend to destroy alignment. A significant role of environmental effects is also indicated by the results of the work of Aryal, Paudel and Saurer (2012) [266], who studied the three merging binary clusters A1750, A3395 and A3528, finding the alignment of galaxies in only one of these clusters (A3395).

It should be also mentioned that it has been noted that the alignment of galaxy orientation can, and even should, evolve over time [148,239,267,268] .From an observational point of view, this means that the alignment of galaxies will also be a function of the z redshift. The work of Stephanovich and Godłowski (2015, 2017) [239,241], directly shows that angular momentum of galaxies in cluster increases with time. Stephanovich & Godłowski (2015, 2017) [239,241] could explain the results of (Song & Lee 2012) [269] paper, who found that the alignment profile of cluster galaxies drops faster at higher redshifts. The results of Stephanovich and Godłowski (2015, 2017) [239,241] are also consistent with those of Hao et al. (2011) [270] who found that alignment of Brightest Cluster Galaxies decreases with redshift. It can also explain the results of the work of Yadav, Aryal and Saurer (2017) [110], who, while studying six dynamically unstable Abbel clusters, found no alignment in them. These clusters are young, so their angular momentum is expected to be small. However, Rong (2015) [271] analyzed four young galaxy clusters and found alignment in them. This may indicate that environmental effects can play a significant role in such facilities.

The methods used in the study of galaxy orientation are universal in the sense that they can be easily adapted to study the problem of orientation of galaxy structures such as groups or clusters of galaxies, as well as to study the relationship between the orientations of clusters and the orientation of their individual members (Godłowski and Flin 2010) [272]. Similarly, it is possible to study the relationship between the orientations of clusters and the distinguished directions, both related to the structure of the cluster, such as the direction to the center of the supercluster or the direction of the line connecting the two brightest galaxies in the cluster, and directions unrelated to the structure being studied, such as some chosen direction in space. It is also possible to study the Binggeli effect, i.e. the relationship between the positions of large axes of galaxy clusters and the directions of their neighbors ([65], see also Smargon 2012 [273] for more modern review)). In the case of studying the latter effect, the Kolmogorov-Smirnov test and the linear regression method are particularly useful (Godłowski and Flin 2010, Biernacka, et al 2015) [272,274]. The paper Godłowski & Flin (2010) [272] shows that the results concerning the analysis of the distribution of position angles of groups of galaxies belonging to the Local Supercluster, their correlation with the direction of the line connecting the two brightest galaxies in the cluster and the direction to the center of the local supercluster, and the relationship between the positions of the large semi-axes of the groups of galaxies and the direction to their neighbors (the Binggeli effect) are consistent with the ΛCDM model, in which structures are formed as a result of hierarchical grouping. They indicate that the two most massive galaxies form first, and then other galaxies form around them, following a hierarchical clustering scenario.

6. Discussion and Conclusions

This survey discusses research on the orientation of galaxies. Studying the orientation of galaxies is one of the most effective methods for testing galaxy formation scenarios. Since groups and clusters of galaxies do not usually rotate, studies of the orientation of galaxies give us also information about the angular momentum of such structures, as they are determined by the angular momentum of their member galaxies. Therefore, observational results on the orientation of galaxies and their structures at different scales were discussed and compared with both numerical simulations and predictions of galaxy formation and structure scenarios. The improvement of old and the introduction of new methods of examining the orientation of the result, together with the development of observational techniques, which made it possible to increase the number of analyzed objects and the use of high-quality catalogue data, allowed for the systematization of the existing results, while allowing for an in-depth verification of galaxy formation scenarios and their structures.

The current state of research indicates that not only galaxies, but also pairs and compact groups of galaxies have non-vanishing angular momentum, mainly due to their orbital motions. On the other hand, for larger structures, there is a relationship between angular momentum (and thus the orientation of galaxies in structures) and their sizes, mass, and richness of galactic components. In structures with masses of order of masses of groups of galaxies, one does not observe the alignment of the orientation of galaxies, while in clusters and superclusters it has been observed, which indicates a non-zero total angular momentum. This picture is also consistent with the results of numerical simulations. Larger-scale studies show even the possibility of large-scale alignment. However, the real observational picture is not so simple, as it has been shown that environmental effects and the probable temporal evolution of the alignment of galaxy orientation have a significant impact here.

Scenarios for the formation of galaxies and their structures are able to explain a number of theoretical problems and observational results. Unfortunately, none of the known models of galaxy formation and structure can so far explain all the observed properties of the objects under consideration at the same time. Of course, the increase in the alignment of galaxy orientations with the size of the structure favors models that predict such a relationship as the tidal interaction scenario in the hierarchical clustering model or the Li model. However, it should be emphasized that currently the most consistent with the obtained results is the modified hierarchical grouping model, taking into account the tidal interaction scenario. This scenario predicts the observed increase in the alignment of the orientation of galaxies in structures with their sizes and explains observations indicating that the direction of angular momentum relative to the main plane of a large-scale structure depends on its mass. However, the most significant is that it is the only model in which dark matter naturally appears. It also explains the dependence of the orientation of galaxies and their structures on the matter around them. Its biggest drawback, however, is that it has fundamental difficulties in explaining the formation of large-scale structures larger than a few tens of megaparsecs.

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