Investigation of galactic alignment in Local Supercluster galaxy clusters

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ABSTRACT

We investigate the orientations of the galactic axes within 18 selected clusters, substructures of the Local Supercluster. For every cluster we map the parameter $\Delta_{11}$ describing the alignment of the galactic axes with respect to a chosen cluster pole, divided by its formal error $\sigma(\Delta_{11})$ [$s = \Delta_{11}/\sigma(\Delta_{11})$]. The cluster pole coordinates change along the entire celestial sphere. The resulting maps are analysed for correlations of their maxima with directions from the cluster centre to (i) the derived 'physical' cluster poles, (ii) the Local Supercluster centre, (iii) the Virgo A centre and (iv) the Earth, i.e. along the line of sight (LOS). The strong maxima – with one exception – exist only for non-spiral (NS) subsamples, with the maximum well correlated with the LOS direction. Another of the studied directions may occur close to the maximum only if these directions are close to the LOS and they do not correlate with other features visible on the maps. For clusters with a clearly defined maximum of $s$ below 3.0 the conclusion generally does not change. For the spiral (S) subsamples the maps are usually at the random noise level. In these cases a weaker, but still existing correlation with the LOS is observed and no other evident correlations are noted. We conclude that a strong systematic effect, generated by the process of deprojection of a galactic axis from its optical image, is present in the catalogue data. With the use of a simple model for the systematic effect we are able to reproduce the main characteristic features of the maps for non-spiral galaxies. We note, however, that a few clusters show significant differences with respect to this model.

Key words: galaxies: clusters: general – galaxies: formation – cosmology: observations.

1 INTRODUCTION

Some scenarios of cosmological structure evolution predict that the orientation of galactic axes in clusters should favour a certain direction while in other scenarios galaxies are expected to be randomly oriented (cf. Shandarin 1974a, b; Wesson 1982; Silk & Efstathiou 1983; Dekel 1985). Attempts to reveal any deviation from isotropy have been performed over the past years with different, and sometimes contradictory results. The work done before 1985 is described by MacGillivray & Dodd (1985), who point out that most studies agree on a random galactic distribution within the Local Supercluster (LSC) plane, however they suggest that galactic planes can be oriented preferentially parallel to the LSC plane at some distance from it. In an important paper Kapranidis & Sullivan (1983) analysed samples of bright spirals belonging to the LSC and found no strong evidence for alignment of these galaxies.

However, Jaaniste & Saar (1977, 1978) claimed the existence of a mean perpendicularity of galactic planes with respect to the LSC plane. Since the earlier approaches were based mostly on analyses of highly inclined and edge-on galaxies, Jaaniste & Saar took all galaxies into consideration, including the face-on ones. This approach was critically discussed and modified by Flin & Godłowski (1986). These authors and later Godłowski (1993, 1994) analysed large galactic samples within the LSC and came to the conclusion that there exists a preferential orientation of galactic planes perpendicular to the LSC plane and that there is evidence for aligning the galactic rotation axes along the direction toward the Virgo cluster centre. The comparison of the alignment properties of spiral and non-spiral galaxies reveals the physically unexpected conclusion that spirals exhibit weaker alignment. This occurs in spite of the fact that the alignment should result from the correlated galactic angular momenta, in the cluster and the spiral galaxies carry substantial angular momenta, allowing for more precise determinations of spatial orientations to measure such correlations.

The recent study of Parnovsky, Karachentsev & Karachentseva (1994) used both the analysis of galactic position angles and the directions of galactic axes obtained from deprojections of images in the UGC and ESO catalogues. Additionally, the catalogue of flat edge-on galaxies compiled by the same authors was used. They detected an anisotropy with the distribution of the galactic axes forming a three-axial ellipsoid, showing an excess of about 20 per
Orientations of galactic axes in galaxy clusters

cent in the direction (4–6h, 20–40°), and a deficit of about 25 per cent in the direction (13–15h, 30–40°). The results are in general agreement with the earlier result of Fliche & Souirau (1990) for orientations of the extended H_1 galactic envelopes and the ‘cosmic pole’ at (5h30m, 7°) derived from distant quasars. Later discussion by Flin (1995) points out that the anisotropy direction found by these authors is essentially the same as the result of Flin & God- 

Several aspects of galactic orientations within separate clusters were investigated in a few ways. There seems to exist compelling evidence for strong alignment of a cD galaxy with its cluster, and the effect is stronger in more elongated clusters (Struble 1987, 1990; Mandzhos 1987; van Kampen & Rhee 1990; Trevese, Cirimele & Flin 1992; Han, Gould & Sackett 1995). Muriel & Lambas (1992) showed the existence of systematic effects in orientations of galaxies with respect to their neighbours. For spiral galaxies the effect exists with respect to the nearest neighbour, while for elliptical galaxies this is also true for all neighbours. For spiral galaxies the effect is stronger in more elongated clusters (Struble 1987, 1990; Mandzhos 1987; van Kampen & Rhee 1990; Trevese, Cirimele & Flin 1992; Han, Gould & Sackett 1995). Muriel & Lambas (1992) showed the existence of systematic effects in orientations of galaxies with respect to their neighbours. For spiral galaxies the effect exists with respect to the nearest neighbour, while for elliptical galaxies this is also true for all neighbours. For spiral galaxies the effect is stronger in more elongated clusters.

The work carried out so far, claiming the detection or non- detection of a galactic alignment in galaxy clusters and other LSC substructures, with discrepant alignment characteristics, requires further study and clarification. Since the large-scale correlations between galactic orientations can be decreased by mixing several differently oriented substructures, the investigation of separate clusters should reveal a much clearer picture of the preferred orientation, if any. Therefore, the present work was originally intended to investigate the orientations of the galactic axes within 18 selected clusters, substructures of the LSC, based on data from Tully’s (1988) Nearby Galaxy Catalog (Section 2). For the majority of these clusters the number of galaxies is not very large. For this reason we have decided to use the statistical parameter of the Fourier test, , describing the preferential orientation of galactic axes with respect to the main axis of the cluster reference frame (Flin & Godlowski 1986; Godlowski 1993, 1994; see Appendix B). In Section 3, for every investigated cluster, we map the value of divided by its formal error (Appendix B), with the cluster pole coordinates changing along the entire celestial sphere. The resulting maps are analysed for correlations of the with directions from the cluster centre to (i) the derived cluster poles, (ii) the Local Supercluster centre, (iii) the Virgo A centre and (iv) the Earth, i.e. along the line of sight (= LOS). For any cluster we divide the full sample according to morphological type into spiral (S) and non-spiral (NS) subsamples. The strong maxima of above 3.0, with one exception occur only for the NS subsample, where the maximum is well correlated with the LOS direction. The maxima are correlated with other directions when those directions are close to the LOS. These directions do not correlate in a clear way with other features visible on the maps. For structures with a clearly defined maximum below 3.0 the conclusion generally does not change. For the S subsamples the maps are often at the noise level with maxima of = 1.0. In these cases no clear correlation of the considered directions and features on maps may be seen. We conclude that a strong systematic effect, generated by the process of deprojection of a galactic axis from its optical image, is present in the catalogue data. It can mask any existing weak alignment in the analysed clusters. The divergences from the expected form of the map observed in some cases may indicate the existence of non-random galactic distributions. The effects however are too weak to be considered quantitatively with the present method. In Section 4, with the use of a simple model for this systematic effect, one is able to reproduce the main characteristic features of the maps for non-spiral galaxies. A short summary and discussion is given in the last section (Section 5). The present analysis provides a firm argument, that one should be very careful when using methods involving reproductions of galactic axis orientations from the shapes of their images in statistical investiga- 

tions. The available data for non-spiral galaxies are subject to large systematic errors. The use of such data in the alignment analysis for samples distributed over large parts of the sky could lead to the detection of spurious alignments toward regions containing the highest numbers of galaxies. The analysis of galactic position angles is free of such systematic effects.

2 OBSERVATIONAL DATA

We considered a galactic sample selected from Tully’s (1988) Nearby Galaxy Catalog, including LSC galaxies with radial velocities – corrected for the solar motion – smaller then 2800 km/sec. This catalogue provides estimates for LSC galaxies and the derived galactic axis inclination to the LOS. The galactic position angles necessary in our analysis are not available in Tully’s catalogue and were therefore taken from Nilson (1973, 1974), Lauberts (1982) and Lauberts & Valentijn (1989). For about 10 per cent of the considered objects the position angles are not available in any source. However, in general these are nearly face-on galaxies and their position angle values have only negligible effects on the derived galactic axis orientations. For the numerical computations below we have taken these position angles at random from the uniform distribution. Tully claims that the data from his catalogue is free of the Holmberg effect, thus no further correction for that effect is introduced into the analysis.

It is well known that the galactic brightness is a very poor distance indicator for neighbouring galaxies. For this reason Kapranidis & Sullivan (1983) in their study of galactic alignment obtained large differences between samples selected according to radial velocities and brightness (see also Flin & Godlowski 1986). Therefore knowledge of the group membership derived from radial velocities is crucial for a serious analysis. Under present considerations we have selected clusters of galaxies from Tully’s catalogue for which there is information on group membership. We have taken into account all clusters which consist of at least 40 galaxies. We analysed separately the samples including all cluster galaxies and two subsamples selected according to the galactic morphological type. We extracted spiral galaxies as one subsample (S) and non- spiral, mostly elliptical ones as the second subsample (NS). The clusters considered are labelled with Tully’s numbers, while the names of the widely known ones are given in parentheses: 11 (Virgo), 12 (Ursa Major), 13, 14 (Coma), 15, 17, 21 (Leo), 22, 23, 31 (Antila–Hydra), 41, 42, 44, 51 (Fornax–Eridanus), 52, 53 (Horatio), 61 (Telescopium), 64. An orientation sketch of the LSC of galaxies with indicated positions of the discussed galactic clusters –substructures of the LSC – is presented in Fig. 1. Detailed lists of the galaxies in the investigated groups can be obtained upon request from one of the authors (WG).

In studies following the Jaaniste & Saar (1977, 1978) approach a
crucial point is to obtain a correct value for the galaxy inclination angle $i$. A formula enabling derivation of that angle from the observed axial ratio $q$, valid for oblate spheroids, is provided by Holmberg (1946) as
\[ \cos^2 i = (q^2 - q_0^2)(1 - q_0^2)^{-1}. \]
Tully (1988) in the NGC catalogue used this formula with $q_0 = 0.2$ for obtaining inclination angles. Only in a statistically insignificant number of cases has he obtained inclinations from other information, such as the form of rings or spiral structure. Then he increased the obtained values of $i$ by 3°, in accordance with the empirical recipe given by Aaronsen, Mould & Huchra (1980). Let us note that Kapranidis & Sullivan (1983) used such a formula (without the mentioned recipe ‘+3°’) only for spirals. Heidmann, Heidmann & de Vaucouleurs (1971) noticed that the value of $q_0$ depends on the galactic morphological type and consequently should vary for different types of galaxies: for spirals $q_0$ should be less than 0.2, while for elliptical galaxies it should be significantly higher. For this reason Flin & Godłowski (1986) and later Godłowski (1993, 1994) considered the ‘true’ axial ratio $q_0$ to depend on the galaxy morphological type. However, as we argue later, it may be questioned whether such a simplified approach can work reasonably well.

3 TESTING THE GALACTIC ORIENTATIONS IN CLUSTERS

3.1 The data analysis method

Let us briefly summarize the data analysis method of Flin & Godłowski (1986; see also Godłowski 1993, 1994) used for the investigation of possible galaxy alignments in LSC clusters. In the analysis one uses the supergalactic coordinate system ($L, B, P$) with the basic great circle (‘meridian’) chosen to pass through the LSC centre in the Virgo cluster. For any galaxy we consider two parameters: the galactic position angle $p$ and the inclination angle $i$. With the use of these angles two orientation angles are determined: $\delta$, an angle between the normal to the galaxy and the LSC plane, and $\eta$, an angle between the projection of this normal at the LSC plane and the direction toward the LSC centre. In the present analysis the method was applied for angles defined with respect to the individual galaxy cluster main plane instead of the LSC plane. The distributions of the two angles $\delta$ and $\eta$ can be analysed using...
Figure 2 – continued
statistical tests from Flin & Godlowski (1986), briefly summarized in Appendix B. Within this method, based on deprojection of galactic images, one obtains two possible vectors normal to the galactic plane and both solutions are considered in the analysis (Jaaniste & Saar 1977). The method was previously used by one of us to study the galactic alignment inside the whole LSC. However, when we consider individual clusters the number of galaxies involved may be small in some cases and not all statistical tests described by Flin & Godlowski (1986) will work well (e.g. the $\chi^2$ test requires the expected number of data per bin to equal at least 7; see, however, Snedecor & Cochran 1967 and Domanski 1979). We base our present work on a test involving the Fourier coefficient $\Delta_{11}$ (cf. Appendix B). The value of $\Delta_{11}$ characterizes the mean alignment of galactic planes with respect to the chosen axis of the reference frame. The positive value of $\Delta_{11}$ obtained during the analysis of the angle $\delta$ appears when the galactic rotation axes tend to be perpendicular to the cluster plane, and for negative values these axes are preferentially parallel to that plane.$^1$

As described in Appendix A, the galactic cluster main plane and the respective axis perpendicular to the cluster main plane can be derived by assuming that the galactic cluster is a three-axial spheroid with Gaussian density distribution along each axis. We establish directions of these axes in the cluster considered by fitting the three-dimensional galactic distribution to galactic positions taken from Tully’s catalogue. As the actual clusters are often quite irregular and subject to inevitable galactic distance errors, the derived axes are rather formal ones and only sometimes contain physical information about the cluster gravitational potential structure. In the analysis below, we allow for all possible orientations of the main axis of the cluster along the celestial sphere. Of course, this axis is not related to the previously mentioned ‘physical’ axes. For each particular choice of the cluster pole the value of the Fourier parameter $\Delta_{11}$ for the angle $\delta$ is derived in order to seek the maximum value of $|\Delta_{11}|$. Because we change the ‘pole’ position along the whole sphere, there is no need to repeat the analysis for the angle $\eta$. Maps of the obtained $\Delta_{11}$ are presented in supergalactic coordinates $L$ and $B$ in Fig. 2. More precisely, we plot the value of $\Delta_{11}$ divided by its standard deviation $\sigma(\Delta_{11})$, $|\Delta_{11}/\sigma(\Delta_{11})| > 1$. It is sufficient to present one hemisphere only, the second one is obtained by reflecting oppositely directed poles. Next to each map the number of the cluster considered, the number of galaxies considered and the maximum value of $|\Delta_{11}/\sigma(\Delta_{11})|$ in the map are given. For S and NS galaxies, the respective symbol is positioned after the indicated number of galaxies. For presentation in Fig. 2 we selected four clusters (11, 15, 22, 23) with different characteristic features; the full set of maps for all 18 clusters is provided in Appendix C. For each cluster, maps are provided for all galaxies and for both S and NS subsamples. The maps are presented in the order of decreasing maximum value of $|s|$. On each map we denote crucial directions, as seen from the centre or toward the centre$^2$ of the considered cluster, for (i) the three derived cluster poles (cf. Appendix A), (ii) the direction to the Local Supercluster centre, (iii) the direction of the Virgo cluster centre and (iv) the line of sight to the Earth (=LOS). Data from the respective fits for all 18 clusters are summarized in Table 1, including the cluster number according to Tully, numbers of all, S and NS galaxies in the cluster,

$^1$ If one calculates $\Delta_{11}$ for the angle $\eta$, the value of $\Delta_{11} < 0$ occurs when the projection of the galactic rotation axis at the plane of the cluster is preferentially oriented perpendicular to the zero-point direction of $\eta$, and for $\Delta_{11} < 0$ the projection tends to be directed along this direction.

$^2$ We chose one of the symmetric directions seen on the presented hemisphere.

position of the Earth as seen from the cluster centre ($L_E, B_E$) and its distance $R$ in Mpc (assuming $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$), and the position of the parameter $s$ maximum on the map for all galaxies, ($L_{\text{max}}, B_{\text{max}}$), followed by the corresponding value of that parameter.

### 3.2 Analysis results

In the majority of the clusters considered we observe two ‘hills’ of positive values in opposite directions on the celestial sphere separated by a circular ‘valley’ of negative values (see in Fig. 2 and Appendix C). The positive hill is expected to appear on the map if the direction of the galactic cluster axis is close to the direction of galactic axis alignment. If we take the considered axis perpendicular to that direction, the alignment is mostly perpendicular to the axis and we observe negative values of $\Delta_{11}$. For the alignment parallel to a single axis in the cluster the depth of the negative valley on the map should be smaller than the height of the hills. In the case when the galactic axes align uniformly along the plane, one expects to find negative holes in the directions perpendicular to that plane, separated by a somewhat less pronounced positive ‘bank’ for the cluster axis directions chosen in the considered plane. Thus the structure most often observed (see cluster 11 in Fig. 2a) could be produced if the galactic axes tended to align along the line joining the considered hills, and then the observed alignment effect could often be interpreted as statistically significant. Below we will argue against such an interpretation and we suggest that a systematic effect along the line of sight may be to a large extent responsible for the structures visible on the maps. One should note, however, that the picture with positive hills surrounded by negative valleys is not a strict rule for all clusters. In some statistically less significant cases, like cluster 23 in Fig. 2, one has separate negative minima surrounded by a circle of positive values. Sometimes the relative values of positive and negative maxima do not fit the above described picture well (for example cluster 52 in Appendix C with nearly equal amplitudes). For cluster 15, on the map for all galaxies (Fig. 2a) the observed maximum alignment direction does not correlate with the LOS and in cluster 22 we do not see any significant peaks.

A significant difference is claimed to exist between alignment characteristics of the spiral and non-spiral galaxies (e.g. Flin & Godlowski 1986). Therefore, in the next step of the analysis we consider differences between such subsamples in each cluster (Fig. 2; Appendix C). For NS galaxies one generally observes a positive peak strongly correlated with the LOS direction, surrounded by a valley of negative $s$. An exception is cluster 52, where a pronounced negative ‘peak’ is encountered. For spiral galaxies, a different picture is common. In general one does not observe the above 3r alignment effects (i.e. with $s > 3.0$). Usually the obtained picture is consistent with a random distribution appended with a very weak systematic correction along the LOS. An exception is cluster 15, where we observe a pronounced positive peak far from the LOS, which could be an indicator of real alignment.

In Fig. 2 and Appendix C, an evident strong correlation of the positive maximum with the LOS direction exists for NS galaxies. It is clear that the same correlation on the maps for all cluster galaxies is to a large extent generated by the NS component. In addition, because of the special position of the Earth with respect to the investigated clusters, the LOS and the Virgo cluster direction are often close to each other (cf. Fig. 1). In the clusters considered, a coincidence between the Virgo direction and the alignment
maximum occurs only if the Virgo direction is close to the LOS, and never happens if it is far from the LOS. In a few cases where the Virgo direction is close to this maximum, the LOS is generally somewhat closer. This fact suggests that a systematic error in determining the galactic axis inclination angle is present in Tully’s catalogue which was used for this analysis. The effect – turning galactic ‘faces’ toward the observer to produce the observed ‘alignment’ – is much more pronounced for NS galaxies, but can also be detected on the maps for the S ones. The last statement can be checked by inspecting of all maps presented in Appendix C for the S subsamples. In the following section we propose a simple model which allows us to reproduce the characteristic systematic effects seen on the maps.

4 MODELLING THE SYSTEMATIC EFFECT CONSIDERED

In order to evaluate quantitatively the systematic effect considered, we have performed a simple modelling of the anisotropic galactic distribution in order to reproduce Tully’s catalogue data. Our null hypothesis is that in fact we have an isotropic distribution of galaxy angular momenta and any preferred orientation arises because we favour the LOS direction in elaboration of the observational data. This fact suggests that the effect should be expressed as a function of the galaxy inclination angle cosine \( \mu \). Thus, we proceeded in the following way. For any cluster considered the galactic spatial positions were not modified. We considered the same distribution of galactic poles for all clusters, consisting of an isotropic part and a simple anisotropic correction along the LOS, proportional to \( \mu \) (i.e. we consider only the first two terms of the distribution expansion in powers of \( \mu \); an example with included terms \( \propto \mu^2 \) is analysed in Appendix D). The assumed normalized probability distribution has the form

\[
F(\mu) = \frac{1}{1 + A} + \frac{2A}{1 + A} \mu. \tag{4.1}
\]

\( \mu \) is the cosine of the angle between the LOS and the galactic pole and the distribution exhibits rotational symmetry along the LOS. For each galaxy in the analysis one uses solutions with both positive and negative values of \( \mu \), but, due to symmetry, the range \( 0 < \mu < 1 \) is considered in equation (4.1). The anisotropic part has a simple form with the (positive or negative) amplitude parameter \( A \).

If the effect of anisotropy is systematic it should influence all galaxies in the catalogue, not only those contained in the clusters discussed. Therefore, for determination of the amplitude \( A \) we considered all LSC galaxies from Tully’s catalogue. All, S and NS galaxies were considered separately and the derived amplitude \( A \) is appended with the respective index ALL, S or NS. Let us note that with the \( A \) obtained it was possible to derive the systematic effect for the whole LSC to have a similar \( \Delta_{11} \) to the value derived from the original data. For all galaxies, the best fit gives

\[
A_{\text{ALL}} = 0.7. \tag{4.2}
\]

An integral amplitude of the anisotropic part is

\[
\int_0^1 2A_{\text{ALL}} \mu(1 + A_{\text{ALL}})d\mu = 0.41.
\]

The fit quality of the data from the Tully catalogue for all LSC galaxies can be evaluated by an inspection of Fig. 3 for galactic orientation angles \( \delta \) and \( \eta \). In the figure, we present the catalogue data superimposed over the ‘theoretical’ distribution derived as a mean from 1000 simulated catalogues using the distribution (4.1) with the amplitude \( A \) given in (4.2).

The discussion in the previous section notes a significant difference between distributions for spiral and non-spiral galaxies. For the spiral galaxies our fitting procedure yields a much smaller value of the amplitude \( A \):

\[
A_{S} = 0.15. \tag{4.3}
\]

while for the non-spirals

\[
A_{NS} = 20.0. \tag{4.4}
\]

One should remember that for the spiral galaxies some low-brightness face-on spirals may be missing and the obtained \( A_{S} \) may be underestimated.

With the use of the derived average values for \( A \) (equations 4.2–4.4), in Fig. 2 and in Appendix C we plotted the maps obtained for

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Table 1. A list of analysed clusters: the respective numbers (\( N, N_{S}, N_{NS} \)), cluster positions (\( L_{c}, B_{c}, R \)), the LOS position on the presented map (\( L_{c}, B_{c}, R \)), the maximum s position on the map (\( L_{\text{max}}, B_{\text{max}} \)) and the value of this maximum.

<table>
<thead>
<tr>
<th>Cluster No</th>
<th>Object No</th>
<th>Position</th>
<th>LOS</th>
<th>Maximum</th>
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<td>227</td>
<td>86</td>
<td>11.7</td>
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<td>123</td>
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the clusters considered with the model distribution (4.1), to be compared with the real data. In each case we derived only one model map, and this map – including the statistical fluctuations – is presented. One may note that our simple model reproduces the original data for clusters with large maxima of \( \Delta_{11} \) relatively well and thus provides a strong argument for the presence of the suggested systematic effect. For spiral galaxies the maps are often at the 1\( \sigma \) level, but quite often the simulated map is similar to the real one with the LOS close to the maximum on the map. However, in some cases noticeable deviations between the simulated and real maps exist. In some clusters the expected significant maximum along the LOS does not exist (cf. clusters 22 or 15 in Fig. 2). Also, the depth of a negative valley surrounding the maximum changes in some cases more significantly than expected for a uniform and isotropic galactic distribution and the observed maximum is much higher then expected from the model (cf. NS cluster 11). In our opinion, the large value of \( A_{NS} \) obtained proves that Tully’s procedure for derivation of the galactic axis inclination provides values not entirely related to the real galactic orientations. Probably his use of a mean galactic ellipsoid form for such galaxies is inappropriate.

Finally, we would like to stress that the model presented is not expected to reproduce all details seen on the maps. Beside the statistical fluctuations, the observed deviations between real and model maps can reflect not only the actual galactic alignments, but also the fact that the systematic error in the catalogue may have a somewhat different form from the simple test distribution introduced in the equation (4.1) and/or can arise from fine galactic morphological type variations in individual clusters, leading to slightly different systematic effects. An example of a more thorough analysis of the problem is presented in Appendix D for the Virgo cluster.

5 FINAL REMARKS

We studied the alignments of the galactic axes in 18 clusters from the LSC with a method based on the analysis of deprojected galactic axis orientations. The considered statistical parameter \( \Delta_{11} \) describes the alignment of the galactic axes along the given direction. Mapping of this parameter in all directions on the sky shows that the most evident alignment occurs along the line of sight, at least in the majority of statistically significant cases. We interpret this finding as the result of a systematic error in the galactic axis determination in the Tully (1988) catalogue.

The anisotropy modelling of the previous section shows the possibility of obtaining a reasonable fit to the data with the simple model (4.1) and the same value of the anisotropy parameter \( A \) for all clusters. One may note that the introduced anisotropy is proportional to the galactic axis projection on the LOS, i.e. the derived galactic distribution underestimates the number of edge-on galaxies. In Tully’s catalogue this effect is very strong for non-spiral galaxies (\( A_{NS} = 20 \)), but it can also be noticed in the subsample of spiral galaxies, where \( A_s = 0.15 \). The analysis of the maps for spiral galaxies, where the systematic effects are much weaker, does not reveal any meaningful correlation of the considered directions – other than the LOS – with the characteristic features of the maps. Possible problems with deprojection of elliptical galaxies were noted by some authors previously (cf. Kapranidis & Sullivan 1983). In the present paper we provide convincing proof for such an effect to exist in Tully’s catalogue. In our opinion the discussed LOS effect arises during computation of the inclination angle, where Tully takes the 'true' galaxy axial ratio equal to 0.2 for all galaxies, independently of their morphological type.

Let us mention that, in contrast to our finding, Bahcall, Gukhathakurta & Schneider (1990) claim that no excess of face-on ellipticals and an excess of edge-on spirals exist for the UGC galaxies. The last effect arises probably due to the number of missing face-on spirals. Our positive fit for \( A > 0 \) suggests that either there are very few missing face-on spirals in the Tully catalogue, or the systematic deprojection errors are significant enough for spiral galaxies to compensate for the lack of some face-on galaxies (we do not consider the possibility of a real alignment along the elongated structure of the LSC here).

Let us mention that some previous positive detections of the alignment of galactic axes can be dominated by similar systematic effects to those introduced by methods involving deprojection of galactic images. In particular, in our analysis, the LOS effects are much larger than any actual signal, yielding a spurious galactic alignment with direction to the cluster. When analysing larger samples covering a substantial part of the sky – with objects distributed in a non-uniform way – an effect of this type should introduce alignment of the galactic axes along a direction pointing

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\(^3\) We also performed (Godlowski, in preparation) analysis of galactic orientations in the UGC and the ESO catalogues (Nilson 1973, Lauberts 1982). In order to derive galactic spatial orientations, the Heidmann et al. (1971) recipe for the galaxy shape determination and the standard Holmberg formula for the inclination angle were used. The model (4.1) was fitted to the data obtained. The obtained values of \( A \) were significantly smaller than the ones given in equations (4.2–4.4). This result confirms our conclusion that the de-projection procedure is responsible for the observed systematic effect.
toward the region containing the largest concentration of galaxies. In a similar manner, a deficit of alignment would be produced in the directions of less populated parts of the sky. In our opinion there is no safe approach, excluding the possibility of LOS systematic effects, when attempting to derive galactic spatial orientations for large galactic samples. Alignment studies involving galactic position angles should not be influenced by any systematic effect of the kind discussed in the present paper if gravitational lensing does not play a role.

Of course, our analysis does not rule out the possibility of some real, weak galactic alignments within galaxy clusters. The exceptions from the general picture, involving the systematic effect mentioned in the text, provide some weak evidence for the real alignments existing in a few clusters. For example, the pronounced positive peak for spiral galaxies occurring far from the LOS in cluster 15 may be suspected of representing such a real alignment, see also the discussion of positive and negative maxima in Section 3. However, one should be aware of the fact that the statistical significance of any such exception may be much lower than the value $\Delta_1/\sigma(\Delta_1)$ provided by the map, due to the large number of tested directions, i.e. a large number of statistical trials.

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REFERENCES

Domanski C., 1979, Non-parametric statistical tests. PWE, Warszawa (in Polish)
Flin P., 1995, Comments Astrophys., 18, 81
Hawley D. L., Peebles P. J. E., 1975, AJ, 80, 477
Mandzhos A., 1987, Astrofizika, 26, 321
Mandzhos A., 1987, Astrofizika, 26, 321
Nilson P., 1974b, SvA, 18, 392
Wesson P. S., 1982, Visitas Astron., 26, 225

APPENDIX A: FITTING OF THE GALAXY CLUSTER AXIS

We use the supergalactic coordinate system $(L, B, P)$, where $P$ is the supergalactic position angle defined by Flin & Godłowski (1986). The coordinates of the supergalactic pole in the equatorial system $\alpha_{1950} = 285.5$ and $\delta_{1950} = +16$ are taken from Tammann & Sandage (1976). In our system the basic great circle (‘meridian’) of the supergalactic system is chosen in such a way that it passes through the Virgo cluster centre with coordinates $\alpha_{1950} = 186.25$, $\delta_{1950} = +13.1$ (Tammann & Sandage 1976). In Tully’s (1988) catalogue, galactic distances and their membership in the corresponding groups are given. With the use of these data we derive positions for the galaxies in a cluster in an orthogonal reference frame. To the distribution obtained we fit a triaxial ellipsoid with a Gaussian density distribution along each axis. Through an orthogonalization procedure of the covariance matrix of the distribution considered, we derive the directions of the main axes of the cluster considered.

APPENDIX B: THE APPLIED STATISTICAL PROCEDURES

To check the distribution of galactic orientation angles $(\delta, \eta)$ we applied statistical tests originally introduced to this problem by Hawley & Peelies (1975), later improved by Kindl (1987) and described in detail by Godłowski (1993, 1994). Below, a short summary is presented of the $\chi^2$ test, the Fourier test and the autocorrelation test.

Let $N$ denote the total number of solutions for the galactic axes (two solutions for any galaxy) in a considered cluster, $N_0$ the number of galaxies with orientations within the $k$th angular bin, $N_0$ the mean number of galaxies per bin and, finally, $N_0/k$ the expected number of galaxies in the $k$th bin. In the present derivations we adopted, in most cases, a division for $n = 36$ bins of equal width. As a check, in a few cases we repeated the derivations for different values of $n$ but no significant differences appeared.

The fits of the anisotropy parameter $A$ for all LSC galaxies presented in Section 4 were obtained with the use of the statistical tests described below. The $\chi^2$ test of the distribution involves the value

\[
\chi^2 = \sum_{k=1}^{n} \frac{(N_k - N_0/k)^2}{N_0/k}. \tag{B1}
\]

It is a function of the minimization in model fitting, with the use of the distribution provided by the model, $N_0/k$. In the present paper this test was used for fitting the parameters $A$ from all LSC galaxies and in Appendix D for the analogous fit for the Virgo cluster. The main statistical test used in the present paper is the Fourier test involving the first Fourier mode only. The actual distribution $N_k$ is

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approximated by
\[ N_k = N_{0,k}(1 + D_{11} \cos 2\theta_k + D_{21} \sin 2\theta_k). \]  
(B2)

The coefficients \( D_{11} \) (\( i = 1, 2 \)) are given as
\[ \Delta_{11} = \frac{\sum_{k=1}^{n} (N_k - N_{0,k}) \cos 2\theta_k}{\sum_{k=1}^{n} N_{0,k} \cos^2 2\theta_k}, \]  
(B3)

\[ \Delta_{21} = \frac{\sum_{k=1}^{n} (N_k - N_{0,k}) \sin 2\theta_k}{\sum_{k=1}^{n} N_{0,k} \sin^2 2\theta_k}, \]  
(B4)

with the standard deviation
\[ \sigma(\Delta_{11}) = \left( \sum_{k=1}^{n} N_{0,k} \cos^2 2\theta_k \right)^{-1/2} \left( 2 \left( \frac{n}{nN_0} \right)^{1/2} \right), \]  
(B5a)

\[ \sigma(\Delta_{21}) = \left( \sum_{k=1}^{n} N_{0,k} \sin^2 2\theta_k \right)^{-1/2} \left( 2 \left( \frac{n}{nN_0} \right)^{1/2} \right). \]  
(B5b)

The probability of the amplitude
\[ \Delta_k = (\Delta_{11}^2 + \Delta_{21}^2)^{1/2}, \]  
(B6)

being greater than a certain chosen value is given by the formula
\[ P(\Delta_k) = \exp \left( -\frac{n}{4} \frac{N_0}{N_k} \Delta_k^2 \right), \]  
(B7)

while the standard deviation of this amplitude is
\[ \sigma(\Delta_k) = \left( \frac{2}{nN_0} \right)^{1/2}. \]  
(B8)

From the value of \( \Delta_k \) one can deduce the direction of the departure from isotropy. If \( \Delta_k < 0 \), then, for \( \theta = \delta + \pi/2 \), an excess of galaxies with rotation axes parallel to the cluster plane is present. For \( \Delta_k > 0 \) the rotation axes tend to be perpendicular to the cluster plane.

APPENDIX C: MAPS OF THE PARAMETER S FOR 18 CLUSTERS

The maps of \( s = \Delta_k/\sigma(\Delta_k) \) in supergalactic coordinates \((L, B)\) are presented for all considered clusters (Fig. A1). For each cluster, the maps for real data are presented above the respective maps obtained from our systematic effect modelling. The maps are given for all cluster galaxies and for S and NS subsamples. On each map we indicated important directions, as seen from the centre of the cluster considered: (i) three cluster poles (full star, square and triangle), (ii) the direction to the LSC centre (open circle), (iii) the direction of the Virgo A cluster centre (open square) and (iv) the LOS (asterisk). Near each panel we give the cluster number appended for subsamples with the respective symbol S or NS, the number of galaxies in the (sub-)sample \( N \) and the maximum value of \( s \) on the map.

APPENDIX D: DIFFERENCES BETWEEN THE REAL MAP AND THE MODEL

As an interesting exercise one could apply the model discussed to any particular cluster in order to remove the influence of the systematic effect. Of course galaxies of different morphological types are included in varying proportions in individual clusters and therefore the model anisotropy amplitude parameter \( A \) may vary among them, deviating from the mean value derived by us. Also, the simplified model claiming that the systematic effect is simply due to the term proportional to the galaxy inclination cosine may be a substantial oversimplification in some clusters. Such effects are visible by eye among the maps of Fig. A1. However, as even a very imperfect removal of the LOS effect will not erase the off-axis alignments, we decided to test in one example whether any remaining structures coincide with other characteristic directions of the LSC. When dealing with an individual cluster we fit an axisymmetric LOS anisotropy model involving the next quadratic term of the anisotropy expansion in \( \mu \). Such a procedure enables a better subtraction of the LOS effect, and thus gives us a chance to look for any galaxy alignment non-coinicident with this axis. Thus, instead of the distribution (4.1) we use one involving two first terms of the expansion of \( F(\mu) \) in powers of \( \mu^2 \):
\[ F(\mu) = \frac{1}{1 + A + B} + \frac{2A}{1 + A + B} \mu + \frac{3B}{1 + A + B} \mu^2. \]  
(D1)

We fit this model to the data for our cluster with the largest number of galaxies, the Virgo cluster (cluster 11), in the following way. For any set of parameters \( A \) and \( B \) from the ranges \( 0 \leq A \leq 2A_{LSC} \) and \( -A_{LSC} \leq B \leq A_{LSC} \) we derived an axisymmetric model distribution for test galaxies placed in the positions of the real ones \((A_{LSC} \) is the amplitude fitted within the model) for the respective – all, S, NS – data derived in Section 4 for all LSC galaxies). For any such galaxy distribution, a map of the alignment coefficient \( \Delta_k/\sigma(\Delta_k) \) was provided and subtracted from the map for the real cluster. The solutions were selected that provided the smallest residuals on the map (Fig. D1). On the left side of the figure we presented the maps for real cluster while on the right side we presented the residuals. Of course, our maps generated with the use of the model are subject to statistical fluctuations and the described procedure provides only a good approximation to the best set \((A, B)\).

Inspection of Fig. D1 shows that subtraction of the model distribution does not leave any significant residues for all galaxies \((A = 0.18, B = 0.37)\) and for spiral galaxies \((A = 0, B = 0.13)\), when a rather weak \(2\sigma\) alignment for NS galaxies \((A = 1.6, B = 2.8)\), non-coinicident with any of the tested directions, was found. In this last case the significance of the residual alignment is even smaller than the cited value due to the large number of directions tested. Without a much more thorough study one is unable to state firmly whether any real alignment exists in this cluster.

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Figure C1. (a) clusters 11, 12, 13, 14; (b) clusters 15, 17, 21, 22; (c) clusters 23, 31, 41, 42; (d) clusters 44, 51, 52, 53; (e) clusters 61, 6.
Orientations of galactic axes in galaxy clusters

Figure C1 – continued
Orientations of galactic axes in galaxy clusters

Figure C1 – continued
Figure C1 – continued

Figure D1. Cluster 11: in the left panels the original data are given and in the right ones the residua of our best-fitting models are presented.