SOME PROPERTIES OF GALAXY STRUCTURES

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Abstract. We analysed some properties of galaxies structures based on the PF catalog of galaxy structures (Panko & Flin 2006) and the Tully NBG catalog (Tully 1988). At first, we analyzed the orientation of galaxies in the 247 optically selected rich Abell clusters, having at least 100 members. The distribution of the position angles of galaxies as well as of two angles describing spatial orientation of the galaxy planes were tested for isotropy, applying three statistical tests. We found the relation between the anisotropy and the cluster richness. The relation between the galaxy alignment and the Bautz-Morgan morphological type of the parent cluster is not present. A statistically marginal relation between the velocity dispersion and cluster richness is observed. We also analyzed ellipticities for 6188 low redshift (z < 0.18) poor and rich galaxy structures which have been examined along with their evolution. Finally, we analyzed the Binggeli effect and found that the orientation of galaxy groups in the Local Supercluster (LSC), is strongly correlated with the distribution of neighbouring groups in the scale up to about 20 Mpc. Analysis of galaxy structures from the PF catalog shows quite different situation – the effect is observed only for more elongated structures (e ≤ 0.3). The effect is present in a distance range of about 60 h⁻¹ Mpc.

Key words: galaxies: clusters and groups; galaxies: orientation, evolution

1. INTRODUCTION

The formation of large-scale structures is one of the most important problems in modern astrophysics. There are many theories called scenarios of structure formation (Peebles 1969; Zeldovich 1970; Sunyaev & Zeldovich 1972; Doroshkevich 1973; Shandarin 1974; Dekel 1985; Wesson 1982; Silk & Efstathiou 1983; Bower et al. 2005). In the presently most popular ΛCDM model, the structures were formed from the primordial adiabatic, nearly scale invariant Gaussian random fluctuations (Silk 1968; Peebles & Yu 1970; Sunyaev & Zeldovich 1970). A very important
problem is to distinguish between different models of formation of galaxies and galaxy structures. The orientation of galaxies in clusters is regarded as a standard
test of theories of galaxy and large-scale structure formation. Thus, theories of the
galaxy formation make predictions regarding to the angular momenta of galaxies
(Peebles 1969; Doroshkevich 1973; Shandarin 1974; Silk 1983; Catelan & Theuns
1996; Li 1998; Lee & Pen 2002; Trujillo et al. 2006). Because the angular momenta
are known for a small number of galaxies, the orientation of member galaxies in
their structure can be studied either by the distribution of galaxy position angles
or the orientation of their planes.

Our analysis of the orientation of galaxies is performed on the sample of 247
optically selected rich Abell clusters, having in the accepted cluster area at least
100 members. The distribution of the orientation of the brightest galaxies in
clusters as well as analysis of the cluster ellipticities are presented for a statistically
complete sample of 6188 galaxy structures from the PF catalog (Panko & Flin
2006, hereafter PF). Also we analyzed the orientation of galaxy groups in the
Local Supercluster and the alignment of galaxy clusters.

2. OBSERVATIONAL DATA

Observational data for the present study are taken from the PF catalog of
galaxy structures (Panko & Flin 2006). It was created using the data from the
Muenster Red Sky Survey (Ungruhe, Seitter, Duerbeck 2003, hereafter MRSS),
which is a large-scale galaxy catalog covering an area of about 5000 square degrees
in the southern hemisphere, complete to a magnitude limit of $m = 18.3$. The same
magnitude limit defines the completeness limit for galaxies in the PF catalog. The
MRSS is the result of scanning of 217 ESO plates with $b < -45^\circ$.

The 2D Voronoi tessellation technique (Ramella et al. 2001; Panko & Flin 2006)
was applied to the galaxy catalog to search for overdense regions. As a result, PF
includes 6188 such structures, with at least 10 galaxies in each structure field.
The Voronoi procedure gives only the area and equivalent radius for the overdense
structures, while the PF contains information about their shape and orientation
on the celestial sphere. A covariance ellipse method involving five moments for
the distribution of galaxy coordinates was used to calculate the elliptical shape
describing each structure, as well as the position angle of its long axis. Lists of
galaxies in the magnitude range $m_3$ to $m_3 + 3$, where $m_3$ is the brightness of the
third brightest galaxy in the structure area, and the rectangular coordinates $x$ and
$y$ of galaxies were used to calculate the semiaxes $a$ and $b$ of the resulting ellipses,
the ellipticity parameter and the position angle of the long axis of each structure.

Since the MRSS does not contain galaxy distances, in order to obtain distance
estimates for the PF structures, we calibrated the $(\log z) - m_{10}$ relation following
Dalton et al. (1997). The first step of the procedure was to compare the positions of the
structure centers, as given in the PF catalog, with those in the ACO (Abell et al. 1989) and APM clusters (Dalton et al. 1997) If the distance between
the centers of the PF and ACO clusters was less than 0.5 of the PF equivalent
cluster radius, the two objects were considered as identical. More than 1000 such
identifications were found. Only 466 ACO clusters from the list have measured
redshifts $z$ in NED. This allowed us to calculate the estimated redshifts $z_{est}$. The
calibration of the $(\log z)$ vs. $m_{10}$ relation in the form: $\log z_{est} = a + b m_{10}$ based
on 455 data points is illustrated in Fig. 1 of papers Biernacka et al. (2009) and
Panko et al. (2009a). The structure identification was repeated using a value of
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Fig. 1. The distribution of the position angles (left panels), $\delta_D$ angles (middle panels) and $\eta$ angles (right panels), for the clusters: A2721 – upper panels and A2554 – bottom panels (supergalactic coordinate system, galaxies with $b/a \leq 0.75$). The theoretical distributions (dashed line) and the error bars are also shown.

0.3 of the PF cluster radius as a new criterion of identity. That produced a similar relationship, but based on a smaller number of center coincidences.

We repeated the procedure with the data for APM clusters, taking the measured redshift $z$ from the APM cluster catalog (Dalton et al. 1997). Additional calibration of the $\log z_{\text{est}} - m_{10}$ relation was possible through the comparison of a deeper version of the PF catalog with ACO. The deeper version of the catalog is not statistically complete, because the limiting magnitude of considered galaxies is $r_F = 19.3$. For future work we select the relation: $\log z_{\text{est}} = -3.771 + 0.1660 m_{10}$.

Each particular relation is located within the confidence limits of other relations: but even the most discordant relations give the maximal difference in $z_{\text{est}}$ of only 0.02 for a magnitude limit of $m = 18.3$.

3. METHOD OF INVESTIGATION

There are two methods for galaxy orientation study. In the first one (Hawley & Peebles 1975) the distribution of the observed position angles of major axes of galaxies is investigated. The second approach allowed us to use also the face-on galaxies. This method, based on the de-projection of the galaxy images, was originally proposed by Opik (1970), applied by Jaaniste & Saar (1977) and significantly modified by Flin & Godlowski (1986, 1989) and Godlowski (1993, 1994). In this method, the galaxy’s inclination with respect to the line of sight of the observer, $i$, is considered. Two possible orientations of the galaxy plane were determined, which gave two possible directions perpendicular to the galaxy plane. It is expected that one of these normals corresponds to the direction of galactic rotation axis. Such study gives a four-fold ambiguity in the solution for the angular momentum. Since we have no information on the galaxy spin directions, our analysis is reduced to only two solutions. The inclination angle was calculated according to the formula valid for oblate spheroids (Holmberg 1946): $\cos^2 i = (q^2 - q_0^2)/(1 - q_0^2)$, where $q = b/a$ is the observed axial ratio and $q_0$ is the "true" axial ratio. A standard value of $q_0 = 0.2$ was used. For each galaxy, two angles are determined: $\delta_D$
The relation between the number of galaxies in the cluster $N$ and the value of analyzed statistics ($\chi^2$ – left panels, $\Delta_1/\sigma(\Delta_1)$ – middle panels, $\Delta/\sigma(\Delta)$ – right panels) for the analyzed angles expressed in the equatorial coordinate system (galaxies with $b/a \leq 0.75$). Upper panels – $\delta_D$ angles, bottom panels – $\eta$ angles. The regression lines as well as the bounds of errors at a confidence level of 95% (broken lines) are presented.

- the angle between the normal to the galaxy plane and the main plane of the coordinate system, and
- the angle between the projection of this normal onto the main plane and the direction towards the zero initial meridian. Using the equatorial coordinate system, the following relations are valid between the angles $(\alpha, \delta, p)$ and $(\delta_D, \eta)$:

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

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

where $r = p - \pi/2$. In order to detect non-random effects in the distribution of the investigated angles $\delta_D$, $\eta$ and $p$, we carried out three different statistical tests: the $\chi^2$ test, the autocorrelation test and the Fourier test (Hawley & Peebles 1975; Godłowski 1993, 1994). Studying the distribution of the position angles, face-on and nearly face-on galaxies were excluded from the analysis. In this case, only galaxies with axial ratio $b/a \leq 0.75$ were taken into consideration. In our previous paper (Godłowski et al. 2010), during analysis of $\delta_D$ and $\eta$ angles, we took into account all galaxies, including the face-on ones. In the present paper, also in this case, we take into account only the galaxies with the axial ratio $b/a \leq 0.75$. This means that we exclude face-on and nearly face-on galaxies. We also checked whether the distributions of the investigated angles ($\delta_D$, $\eta$ and $p$) in each individual cluster were isotropic (for details see Godłowski et al. 2010).

4. RESULTS

4.1. Dependence of the alignment on the cluster richness

The expected isotropic distribution of $\delta_D$ and $\eta$ (polar and azimuthal) angles are modified if some galaxies (for example face on galaxies) are excluded from the
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Table 1. The results of the linear regression analysis for angles calculated in the equatorial coordinate system.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\chi^2$</th>
<th>$\Delta_1/\sigma(\Delta_1)$</th>
<th>$\Delta/\sigma(\Delta)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P$</td>
<td>0.025</td>
<td>0.015 34.7 1.4</td>
<td>0.0018 0.0015 1.55 0.15</td>
</tr>
<tr>
<td>$\delta$</td>
<td>0.227</td>
<td>0.044 26.8 4.3</td>
<td>0.0069 0.0024 1.61 0.23</td>
</tr>
<tr>
<td>$\eta$</td>
<td>0.135</td>
<td>0.045 43.0 4.3</td>
<td>0.0059 0.0031 2.31 0.30</td>
</tr>
</tbody>
</table>

analysis. In such situation the expected isotropic distribution should be found from the Monte Carlo simulation. In the paper Godłowski et al. (2010) in the analysis of $\delta_D$ and $\eta$ angles we took into account all galaxies. Fig. 1 in that paper shows the observed and theoretical distributions of the investigated angles ($\delta_D$, $\eta$ and $P$) for the clusters A2254 and A2771. In Figure 1 we present appropriate theoretical and observed distribution of $P$, $\delta_D$ and $\eta$ angles for the same clusters in the case, when the galaxies with $b/a > 0.75$ are excluded. Please note that our plots are very similar to those obtained by Aryal et al. (2007).

Our previous papers (Godłowski, Baier & Mac Gillivray 1998; Godłowski & Ostrowski 1999; Baier, Godłowski & Mac Gillivray 2003 and Godłowski, Szydłowski & Flin 2005) allowed to conclude that the alignment is present only in a number of rich clusters of galaxies, while the clusters with sparse populations do not exhibit this property. However, this suggestion (Godłowski, Szydłowski & Flin 2005; Aryal, Pudel & Saurer 2007) was only qualitative.

Therefore Godłowski et al. (2010) examined the orientation of galaxies in clusters both qualitatively and quantitatively and found a sharp increase of galaxy orientation alignment with richness of the cluster. Both in the present paper and in Godłowski et al. (2010) we analyzed the orientation of galaxies in 247 optically selected rich Abell clusters, having in the area considered as a cluster at least 100 members. In the paper Godłowski et al. (2010) in analysis of the $\delta_D$ and $\eta$ angles we took into account all galaxies (including the face-on ones). Now we present the analysis of $\delta_D$, $\eta$ angles in the case when galaxies seen face-on and nearly face-on are excluded.

The position angles of major axes of galaxy images, as well as two angles $\delta_D$ and $\eta$ describing the spatial orientation of galaxy plane, were tested for isotropy, applying three different statistical tests. We investigated the relation between the values of the applied statistics and the cluster richness for the investigated angles, both in equatorial and supergalactic coordinate systems. The results are shown on Figure 2 and Table 1. We find that the values of the applied statistics increase with the number of member galaxies, which means the presence of the relation between the anisotropy and cluster richness.

The search for connection of galaxy alignment and Bautz-Morgan morphological type of parent cluster gives only a weak dependence. A statistically marginal relation between the velocity dispersion and cluster richness is observed. At almost $3\sigma$ level the velocity dispersion decreases with the Bautz-Morgan type. The effect increases if we restrict the cluster membership to galaxies brighter than $m_3 + 3$, which suggests that this effect is really connected with the clusters. We also repeated the analysis using a sample of galaxies within the magnitude range $m_3 + 2$. There are no significant differences between the results of linear regression for the samples with the magnitude ranges $m_3 + 2$ and $m_3 + 3$. We conclude that excluding from the analysis face-on and nearly face-on galaxies does not change our results.
significantly in comparison to the results of Godłowski et al. (2010) paper. These results, showing the dependence of galaxy alignment on either the cluster richness or other tested parameters, are due to the environmental effect. In our opinion the observed relation between the richness of the galaxy cluster and the alignment is due to tidal torque, as suggested by Catelan & Theuns (1996). One should note, however, that our finding is also in agreement with the prediction of the Li model (Li 1998; Godłowski et al. 2003).

4.2. Alignment of the brightest cluster galaxy with the parent cluster

For 1056 PF structures, which have been identified with ACO (Abell et al. 1989) clusters with known BM morphological types, we studied the alignment of the brightest galaxy with the parent cluster. We investigated for isotropy an acute angle \( \phi \) being the difference between the structure position angle and the position angle of the brightest cluster galaxy (Panko et al. 2009b). Several subsamples were analyzed for isotropy of the \( \phi \) angle. The distance between clusters, as well as the BM morphological types, served for the subsample selection. The isotropy of the distribution was tested by applying statistical tests mentioned above (section 4.1). Only in the case of clusters BM I the distribution was non random; the small excess at small \( \phi \) angles was observed, which means that the brightest cluster member tends to be aligned with the parent cluster. In Figure 3 two distributions of the \( \phi \) angles for clusters of BM types I and I-II are given (Panko et al. 2009b). Moreover the orientation of the tenth brightest galaxies in each structure was checked for the isotropy. The distribution of \( PA_i \) (where \( i = 1,2,3,10 \)) appeared to be isotropic (Panko et al. 2009b). A separate test was performed to establish whether the observed angle in a particular bin deviates from isotropy by more than a standard deviation \( \sigma = \sqrt{N} \), where \( N \) is the number of objects expected in a bin of random distribution.

Separately, the isotropy of the distribution of position angles of 6188 structures, as well as of 1056 PF structures identified with the ACO clusters was tested. No cases were found with a significant deviation from isotropy. Therefore we conclude that the analyzed distributions are isotropic.

4.3. Alignment of galaxy clusters

Binggeli (1982) has found that galaxy clusters tend to point each other. We searched for the Binggeli effect through investigations of the difference between the position angle of a cluster and the direction toward neighbouring structures. The resulting acute angle \( \phi \) was tested for isotropy. Only after restricting our samples to more elongated structures (\( e \leq 0.3 \)) the distributions became anisotropic, with the excess of small \( \phi \) angles, and this indicates the existence of the Binggeli effect. This effect is statistically weak and observed in the case of all 1056 structures, as well as after dividing into BM types. The strongest effect is observed for the BM I and BM III types. The range of the distance, in which the effect has been
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4.4. **Orientation of galaxy groups in the Local Supercluster**

We analysed also the orientation of galaxy groups in the Local Supercluster (Godłowski & Flin 2010). It is strongly correlated with the distribution of neighbouring groups in the scale up to about 20 Mpc. The group major axis is in alignment with both the line joining the two brightest galaxies and the direction toward the center of the LSC. These correlations suggest that two brightest galaxies were formed in the filaments of matter directed towards the protosupercluster center. Afterwards, the hierarchical clustering has led to aggregation of galaxies around these two brightest galaxies. The groups were formed on the same or a few filaments with similar orientation.

5. **CONCLUSIONS**

We investigated the distribution of several parameters connected with the angular momenta of galaxies. In the ΛCDM model, which is the most popular one, the angular momenta of galaxies originate mainly due to tidal torquing of neighbouring galaxies. Our result that the alignment of galaxies in rich clusters increases with increasing of the richness is due to a tidal torque, as suggested by Catelan & Theuns (1996). One should note however, that our finding is also in agreement with the prediction of the Li model (see also Godłowski 2011).

The observed alignment of the brightest cluster galaxy with the parent cluster for BM I type clusters shows a special role played by a gigantic cD galaxy during the evolution of cluster. The alignment of groups in the LSC is observed up to about 20 h⁻¹ Mpc. The major axis of a group is aligned with both the line joining the two brightest galaxies and the direction toward the center of the LSC, i.e., the Virgo cluster. Two brightest galaxies were formed on the filament of matter directed toward the protocluster center. Afterwards, the hierarchical clustering has led to aggregation of galaxies around these two galaxies. The groups were formed on the same or a few filaments of similar orientation. This picture is in agreement with both the prediction of numerical simulation and expectation from ΛCDM models.

The covariance ellipse method is a good tool for cluster ellipticity studies (Bierhacka & Flin 2011). The shape of each structure projected on the celestial sphere was determined using the covariance ellipse method. Analysis of the data indicates that the structure ellipticity changes with redshift. Nearer structures are more round, which can be attributed to virialization processes occurred in not so distant past (see also Struble & Ftaclas 1994).

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