THE ORIENTATION OF GALAXIES IN CLUSTERS

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Summary:

The method of investigating the orientation of galaxy rotation axes in the Local Supercluster originally introduced by Jaaniste and Saar (1977), which takes into account both galaxy position angle and inclination, has been applied to a sample of 2227 galaxies based on UGC and ESO catalogues. We complete also the second independent sample of galaxies taken from Tully Nearby Galaxy Catalog. These sample reach 2367 galaxies. We used new advanced statistical method. We analyze the orientation of galaxies in the whole Local Supercluster and in the reach groups of galaxies taking from NGC catalogue. We found that the distribution of galaxy planes in the whole LSC is anisotropic. Galaxy planes rather tend to be perpendicular to the LSC plane. The projection of galaxy rotation axes on the LSC plane rather tend to point toward the Virgo Cluster center. The distributions the spirals galaxies are different then non-spirals. In the most reach group we observed anisotropy too but the direction deviation from isotropy is rather in the various groups. For the Virgo cluster itself the result is the same as for the whole LSC. Our result support pancake scenario but "hedgehog model" is possible too.

1. Introduction

The investigation of the distribution of galaxy orientation in the Local Supercluster has a long history. Most previous papers showed that distribution is not uniform. These papers mostly based on the analysis of galaxy position angle ρ. Nearly all from this results could be interpreted as parallelism of galaxy planes to the supergalactic plane. When we analyzed distribution of galaxy position angels ρ we my take into account only "edge-on" galaxies, for which this parameter may be determined. Jaaniste and Saar (1977;JS) found that galaxy rotation axes tend to be distributed parallel to the LSC plane. They analyzed not only the distribution of galaxy position angles ρ, but also took into account their inclination i to the observer's line-of sight, so they my included to our analysis galaxies seen "face-on" or nearly "face-on".

The JS is full of inconsistencies as was showed by the preliminary analysis of it. Some of them have already been mentioned in our previous work. Moreover, JS used only angle δ_D, giving the orientation of galaxy planes with respect to the LSC plane. We used also the second important parameter, angle η, which is the angle between the projection of rotation axis on the supergalactic plane and the direction toward Virgo Cluster center. Of course we should remember that for particular galaxies we have 4 solution given angular momentum of galaxies. Consideration of orientation axes only, we may decreases this to the two solutions.

2. Observational data.

We used two independent sample of galaxies. First sample based on UGC and ESO catalogues of galaxies and second taken from Tully "Nearby Galaxy Catalogue" (1988).

In the first sample we take from catalogues "Upsala General Catalogue of Galaxies" (Nilson 1973) and "Upsala Survey of ESO" (Lauberts 1982) all galaxies with know from literature radial velocities (correct for solar motion) below 2600 km/s. For that galaxies we take from these catalogues position on the celestial sphere in equatorial coordinates: α and δ, its magnitude, the diameters a and b of the major and minor axes and the position angle ρ_*. The inclination angle, i.e. the angle between the normal to the galaxy plane and the observer's line-of-sight was computed from the formula: $\cos^2 i=(q^2-q_0^2)/(1-q_0^2)$, which is valid for oblate spheroids (Holmberg 1946). The true axial ratios q_0 are taken from H^2V (Heidman et al. 1971). For peculiar galaxies it was assumed that $q_0=0.2$. Value q is converted to standard, photometric axial ratios which removes the Holmberg effect.

In the second sample we take into account galaxies from Tully NGC catalogue. This catalogue given all necessary data only with exception of position angle. So we was forced take position angles ρ of galaxies from other sources. Data from this catalogue is very well because according Tully they are free of Holmberg effect. Moreover author given the most probably distance of galaxy from us ant what is very important group affiliation. So we may tested orientation of galaxies not only in the whole Supercluster but also in the particulars clusters.

The sample was divided into three groups according to morphological type; groups containing spirals and lenticular galaxies are denoted as "spirals", the remaining ones are denoted as "non-spirals". Both groups together are denoted as "all". Investigating the distribution of galaxy in the LSC it is convenient to express the galaxy position and theirs position angle in the supergalactic coordinate system, instead of the equatorial system. The supergalactic coordinate system is defined (Flin, Godłowski 1986):

a:the coordinates of the supergalactic pole in the equatorial system are: $\alpha=285^{\circ}.5$, $\delta=+16^{\circ}$

b:the basic great circle "meridian" of the supergalactic system passes through the Virgo Cluster center with coordinates (Sandage and Tammann 1976): $\alpha=186^{\circ}.25$, $\delta=+13.1$. In this system we obtain /where $p=\rho-\pi/2$/ :

$\sin\delta_D=-\cos i*\sin B\pm\sin i*\cos p*\cos B$

$\sin\eta=(\cos\delta_D)^{-1}*(-\cos i*\cos B*\sin L+\sin i*(\mp\cos p*\sin B*\sin L\pm\sin p*\cos L)$

3.Angular distribution isotropy tests.

We should check if the distributions of the angles δ_D and η are isotropic. I applied three different statistical tests, following Hawley and Pebbles (1975) and Kindl (1986) but more advanced then in original papers. These are: χ^2 test, the Fourier test and the auto correlation test. In all tests the range of the angle θ (where $\theta=\delta_D+\Pi/2$ or η) was divided into n bins (n=36 - it mean 35 degree of freedom in the χ^2 test).

Let N denotes the total number galaxies (solution) in the sample, N_K the number of galaxies in k-th bin N_0 the mean number of galaxies per bin and N_{0K} expected number of galaxies in k-oh bin. In the χ^2-test the measure of deviation of the observed distribution from the theoretical, isotropic distribution is given by the statistics: $\chi^2=\sum_1^n(N_K-N*p_K)^2/N*p_K$ where p_K is the probability that a chosen galaxy falls into k-th bin.

The Fourier test checks how the departure from isotropy slowly varies with the angle θ. The model is:

$$N(\theta_K)=N_0*(1+\Delta_{11}*\cos 2\theta_K+\Delta_{21}*\sin 2\theta_K+\Delta_{12}*\cos 4\theta_K+\Delta_{22}*\sin 4\theta_K)$$

In original H-P papers the authors check distribution of the position angles. On that situation all probability p_K are equal. When we analyzed distribution δ_D angle probability p_K are not equal. Moreover H-P take into account only first Fourier mode. So our formulas are much more complicate then in H-P papers. If we take into account only first fourier mode then obtain formulas:

$$\Delta_{1J}=\sum_1^n(N_K-N_{0K})*\cos 2J\theta_K/\sum^n N_{0K}*\cos^2 2J\theta_K \quad \text{where} \quad \sum^n N_{0K}*\cos^2 2J\theta_K\approx\frac{n}{2}*N_0 \quad \text{and}$$

$$\Delta_{2J}=\sum_1^n(N_K-N_{0K})*\sin 2J\theta_K/\sum_1^n N_{0K}*\sin^2 2J\theta_K \quad \text{where} \quad \sum^n N_{0K}*\sin^2 2J\theta_K\approx\frac{n}{2}*N_0.$$

The probability that the amplitude $\Delta_J=(\Delta_{1J}^2+\Delta_{2J}^2)^{1/2}$ is greater than a certain chosen values given by formula $P(>\Delta_J)=\exp(-\frac{n}{4}*N_0\Delta_J^2)$. The standard deviation of the amplitude is $\sigma(\Delta)=(2/n*N_0)^{1/2}$. We may found the direction of departure from isotropy or from Δ_{11} or from coefficient F considering the model $N(\theta_K)=N_0(1+F*\cos 2\theta_K)$, (where the F-coefficient is obtained from the fit). If $F<0$, $\Delta_{11}<0$ then an excess of galaxies with rotation axes parallel to the supergalactic plane is observed, whereas for $F>0$, $\Delta_{11}>0$ the rotation axes tend to be perpendicular to the plane. The standard deviation of the F-coefficient is: $\sigma_F=(\sum_1^n(F_K-F)^2/n(n-1))^{1/2}$

Tab.I Orientation of Galaxies in the LSC (UGC ESO catalogue)

		N	χ^2	C	$P(\Delta_1)$	$P(\Delta)$	Δ_{11}	$\sigma(\Delta_{11})$	W_A	$\sigma(W_A)$
δ_D	ALL	4454	48.2	8.70	.030	.048	-.053	.022	0.063	.022
	S	3130	29.6	-0.27	.828	.608	-.006	.026	0.017	.026
	N-S	1324	54.7	22.11	.000	.001	-.164	.040	0.170	.040
η	ALL	4454	51.5	15.60	.001	.003	0.078	.021	-.038	.015
	S	3130	33.5	7.42	.290	.339	0.039	.025	-.010	.018
	N-S	1324	51.8	8.73	.000	.000	0.172	.039	-.104	.027

Tab.II Orientation of galaxies in the LSC (NGC Tully catalogue)

		N	χ^2	C	$P(\Delta_1)$	$P(\Delta)$	Δ_{11}	$\sigma(\Delta_{11})$	W_A	$\sigma(W_A)$
δ_D	ALL	4734	60.3	7.30	.080	.159	-.045	.021	0.039	.021
	S	3270	40.3	-5.98	.973	.852	0.005	.026	-.010	.025
	N-S	1464	71.5	22.60	.000	.001	-.156	.038	0.147	.038
η	ALL	4734	59.7	6.94	.000	.000	0.095	.021	-.059	.015
	S	3270	42.7	-9.49	.032	.107	0.029	.025	-.010	.017
	N-S	1464	87.3	50.85	.000	.000	0.241	.037	-.168	.026

If we take into account next Fourier mode the formulas are:

$$\Delta_{11}=(C*K-U*L)/(A*C-U^2), \qquad \Delta_{21}=(D*L-W*M)/(B*D-W^2),$$

$$\Delta_{12}=(-U*K+A*L)/(A*C-U^2), \qquad \Delta_{22}=(-W*L+B*M)/(B*D-W^2)$$

where

$A=\sum_1^n N_{0k}*\cos^2 2\theta_k$, $B=\sum_1^n N_{0k}*\sin^2 2\theta_k$, $C=\sum_1^n N_{0k}*\cos^2 4\theta_k$, $D=\sum_1^n N_{0k}*\sin^2 4\theta_k$, $U=\sum_1^n N_{0k}*\cos 2\theta*\cos 4\theta_k$, $W=\sum_1^n N_{0k}*\sin 2\theta*\sin 4\theta_k$, $K=\sum_1^n (N_k-N_{0k})*\cos 2\theta_k$, $L=\sum_1^n (N_k-N_{0k})*\sin 2\theta_k$, $Ł=\sum_1^n (N_k-N_{0k})*\cos 4\theta_k$, and $M=\sum_1^n (N_k-N_{0k})*\sin 4\theta_k$

Covariance matrix $C=G^{-1}$ is:

$$C=G^{-1}=\begin{pmatrix} C/(A*C-U^2) & 0 & -U/(A*C-U^2) & 0 \\ 0 & D/(B*D-W^2) & 0 & -W/(B*D-W^2) \\ -U/(A*C-U^2) & 0 & A/(A*C-U^2) & 0 \\ 0 & -W/(B*D-W^2) & 0 & B/(B*D-W^2) \end{pmatrix}$$

It mean for example that:

$$\Delta_{11}=\frac{((\sum_1^n N_k-N_{0k})*\cos 2\theta_k)*(\sum_1^n N_{0k}*\cos^2 4\theta_k)}{(\sum_1^n N_{0k}*\cos^2 2\theta_k)*(\sum_1^n N_{0k}*\cos^2 4\theta_k)-(\sum_1^n N_{0k}*\cos 2\theta*\cos 4\theta_k)^2} -$$

$$-\frac{((\sum_1^n N_k-N_{0k})*\cos 4\theta_k)*(\sum_1^n N_{0k}*\cos 2\theta_k*\cos 4\theta_k)}{(\sum_1^n N_{0k}*\cos^2 2\theta_k)*(\sum_1^n N_{0k}*\cos^2 4\theta_k)-(\sum_1^n N_{0k}*\cos 2\theta*\cos 4\theta_k)^2}$$

$$\sigma^2(\Delta_{11})=((\sum_1^n N_{0k}*\cos^2 2\theta_k)*(\sum_1^n N_{0k}*\cos^2 4\theta_k)-(\sum_1^n N_{0k}*\cos 2\theta*\cos 4\theta_k)^2)^{-1}*\sum_1^n N_{0k}*\cos^2 4\theta_k$$

Moreover we need formulas for probability that analyzed distribution are the same than theoretical one. Let I denote:

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

then formulas for probability is:

$$P(\Delta)=(1+J/2)^2*\exp(-J/2) \qquad \text{where } J=\sum_i^4\sum_j^4 G_{ij}*I_i*I_j$$

The auto correlation test measures the correlations between the number of galaxies in adjoining angle bins. The correlation function is:

$$C=\sum_1^n (N_K-N_{0K})*(N_{K+1}-N_{0K+1})/(N_{0K}*N_{0K+1})^{1/2}$$

In cease isotropic distribution we expect $C=0$. The standard deviation is: $\sigma(C)=n^{1/2}$. The W-coefficient is: $W_B^*=(N_\parallel-N_\perp)/N$ where $N_\parallel$ and $N_\perp$ denote the number of galaxies with rotation axes parallel and perpendicular to the supergalactic plane. $W_B=W_B^*-\bar{W}_B$ where $\bar{W}_B=2p_\parallel-1$. The coefficient W_A is: $W_A=(\Sigma_\parallel N_i/p_i n-\Sigma_\perp N_i/p_i n)/N$, while variance are: $\sigma^2(W_B)=(4p_\parallel(1-p_\parallel)/N)$ and $\sigma^2(W_A)=\sum_A^n((1-p_k)/p_k+1)/(n^2*N)$.

4.The orientation of rotation axis of galaxies in the LSC

Results for the whole Supercluster are presented in the Table I and II. The anisotropy is observed for all and non-spirals galaxies. For "spirals" galaxies situation is not so clear. The shapes of all distributions are of

Tab.III Orientation of galaxies in the clusters δ_D (NGC)

	N	χ^2	C	$P(\Delta_1)$	$P(\Delta)$	Δ_{11}	$\sigma(\Delta_{11})$	W_A	$\sigma(W_A)$
δ_D 11	626	68.8	8.46	.037	.031	-.150	.058	0.091	.057
	454	32.2	2.37	.581	.516	0.033	.069	-.061	.067
	172	125.0	38.54	.000	.000	-.634	.112	0.493	.110
12	332	42.8	1.58	.593	.642	-.082	.080	0.122	.079
	246	35.6	-1.49	.899	.510	-.036	.093	0.102	.092
	86	54.2	-11.72	.357	.638	-.213	.158	0.178	.155
13	128	59.0	7.11	.705	.930	-.074	.129	0.094	.127
	76	64.5	4.90	.978	.766	-.009	.168	-.114	.165
	52	42.2	11.07	.548	.327	-.170	.203	0.400	.199
14	426	40.5	7.32	.126	.359	-.106	.071	0.085	.070
	202	33.4	-0.32	.799	.496	-.020	.103	-.046	.101
	224	37.9	2.12	.074	.179	-.184	.098	0.204	.096
15	130	40.9	4.30	.870	.844	0.067	.128	-.055	.126
	94	34.2	4.12	.120	.343	0.192	.151	-.151	.148
	36	47.3	12.34	.011	.103	-.261	.244	0.196	.240
21	248	49.0	12.60	.000	.003	-.171	.093	0.157	.091
	180	45.4	11.74	.001	.003	-.217	.109	0.178	.107
	68	33.3	-3.88	.142	.490	-.047	.177	0.102	.174
22	126	29.2	-5.76	.748	.652	-.063	.130	0.061	.128
	80	43.9	-11.94	.338	.497	0.043	.164	-.066	.161
	46	25.1	-7.79	.338	.470	-.247	.216	0.282	.212
23	100	44.1	-14.33	.340	.675	0.215	.146	-.229	.144
	74	59.1	-11.78	.074	.198	0.367	.170	-.408	.167
	26	28.4	1.91	.350	.651	-.219	.287	0.279	.282
31	210	59.3	1.66	.004	.021	0.239	.101	-.255	.099
	158	52.4	-0.63	.070	.199	0.232	.116	-.230	.114
	52	38.8	6.95	.012	.035	0.262	.203	-.329	.199
41	192	31.7	5.70	.405	.186	0.072	.106	0.037	.104
	126	25.8	-1.80	.612	.365	0.094	.130	0.046	.128
	66	50.5	-2.88	.014	.090	0.029	.180	0.022	.177
42	230	47.8	-1.31	.113	.137	-.067	.097	0.074	.095
	164	56.3	-7.22	.538	.120	-.071	.114	0.099	.112
	66	43.8	13.93	.081	.016	-.057	.180	0.013	.177
51	228	48.5	5.18	.001	.010	0.011	.097	0.121	.095
	160	36.6	-4.14	.362	.251	-.032	.116	0.115	.114
	68	61.1	6.93	.000	.001	0.111	.177	0.135	.174
52	172	37.4	2.81	.077	.155	-.083	.112	0.089	.110
	128	26.5	-3.07	.305	.512	-.035	.129	0.110	.127
	44	44.8	3.62	.157	.335	-.222	.221	0.031	.217
53	260	49.2	-3.49	.597	.037	0.058	.091	-.030	.089
	182	45.6	-7.89	.327	.131	-.043	.108	0.087	.107
	78	67.2	8.69	.000	.001	0.295	.166	-.302	.163
61	258	40.4	5.82	.002	.020	-.261	.091	0.242	.089
	198	38.2	-2.42	.259	.464	-.152	.104	0.194	.102
	60	37.6	17.93	.000	.000	-.620	.189	0.403	.186
64	102	34.2	1.36	.084	.428	-.050	.145	0.088	.142
	66	33.7	2.35	.533	.637	-.133	.180	0.169	.177
	36	40.8	-2.59	.035	.075	0.101	.244	-.060	.240

the same character. In the case of δ_D the signs of the F-coefficient and Δ_{11} are negative (W are positive). It mean that galaxy rotation axes are parallel to the supergalactic plane. In the case of η the sign of F and Δ_{11}

are positive it mean that projection of rotation axes on the supergalactic plane tend to point toward center of the Virgo Cluster.

In the tab.III and IV we have result for various groups going from NGC

Tab.IV Orientation of galaxies in the clusters η (NGC)

	N	χ^2	C	$P(\Delta_1)$	$P(\Delta)$	Δ_{11}	$\sigma(\Delta_{11})$	W_A	$\sigma(W_A)$
η 11	626	74.8	27.92	.000	.000	0.327	.057	-.192	.040
	454	55.6	16.22	.002	.008	0.218	.066	-.101	.047
	172	77.9	30.19	.000	.000	0.616	.108	-.430	.076
12	332	33.9	8.37	.011	.021	-.076	.078	0.054	.055
	246	28.5	4.54	.278	.132	-.032	.090	0.041	.064
	86	44.6	11.53	.006	.025	-.202	.152	0.093	.108
13	128	41.3	0.81	.124	.175	0.247	.125	-.203	.088
	76	32.9	1.68	.544	.845	0.179	.162	-.184	.115
	52	40.8	-1.46	.153	.073	0.346	.196	-.231	.139
14	426	39.1	7.77	.210	.046	0.028	.069	0.000	.048
	202	35.7	0.63	.157	.071	-.177	.100	0.119	.070
	224	52.4	15.63	.001	.002	0.213	.094	-.107	.067
15	130	40.6	7.08	.532	.169	0.049	.124	0.000	.088
	94	43.9	2.89	.707	.218	-.017	.146	0.021	.103
	36	28.0	7.00	.510	.143	0.224	.236	-.056	.167
21	248	32.5	-7.18	.453	.733	0.087	.090	-.040	.064
	180	38.4	-9.60	.930	.951	0.021	.105	0.022	.075
	68	31.5	4.00	.038	.117	0.262	.171	-.206	.121
22	126	30.6	-8.29	.634	.877	0.102	.126	-.063	.089
	80	34.3	-2.15	.725	.856	0.077	.158	0.000	.112
	46	29.1	-4.52	.784	.916	0.145	.209	-.174	.147
23	100	36.1	7.64	.127	.058	-.143	.141	0.120	.100
	74	29.1	4.81	.369	.253	-.143	.164	0.108	.116
	26	48.8	-2.46	.251	.252	-.143	.277	0.154	.196
31	210	34.8	6.17	.006	.011	0.188	.098	-.086	.069
	158	43.9	5.37	.132	.019	0.096	.113	-.025	.080
	52	38.0	6.85	.009	.014	0.467	.196	-.269	.139
41	192	49.1	2.06	.037	.011	0.207	.102	-.135	.072
	126	40.9	-0.29	.588	.246	0.056	.126	-.032	.089
	66	63.8	13.09	.006	.014	0.497	.174	-.333	.123
42	230	52.7	-7.11	.259	.241	0.018	.093	0.000	.066
	164	38.0	-7.27	.907	.942	-.048	.110	0.012	.078
	66	56.2	4.91	.007	.008	0.183	.174	-.030	.123
51	228	47.1	-3.00	.199	.265	0.166	.094	-.114	.066
	160	37.5	0.20	.829	.839	0.025	.112	-.013	.079
	68	36.8	-1.82	.014	.047	0.498	.171	-.353	.121
52	172	46.1	9.05	.000	.002	0.223	.108	-.186	.076
	128	49.8	-4.81	.005	.018	0.177	.125	-.156	.088
	44	41.1	-6.36	.039	.077	0.356	.213	-.273	.151
53	260	38.2	2.11	.923	.744	0.027	.088	-.031	.062
	182	42.3	-2.40	.875	.383	0.012	.105	-.022	.074
	78	31.8	-1.38	.433	.566	0.062	.160	-.051	.113
61	258	27.5	-4.88	.475	.353	0.090	.088	-.070	.062
	198	39.1	-1.09	.213	.180	0.082	.101	-.101	.071
	60	45.6	0.00	.281	.044	0.117	.183	0.033	.129
64	102	79.4	8.47	.053	.133	0.320	.140	-.275	.099
	66	64.9	2.18	.683	.768	0.149	.174	-.212	.123
	36	66.0	-8.00	.007	.035	0.634	.236	-.389	.167

Tully catalogue. The anisotropy is rather observed but direction of departure is rather for various groups. The most important are: Virgo Cluster (11) where anisotropy is the same then in the whole supercluster, Ursa Major (12) where we observed anisotropy only on the η angle but Δ_{11} and F coefficient are negative (on the whole LSC are positive - because of position on this cluster in the LSC it is going to the "hedgehog model"), and Coma (14) where we don't observe the anisotropy.

5.Conclusions

Our sample is uncontaminated by background objects. The distribution of galaxy planes tend to be perpendicular to the LSC plane. The projection of rotation axes on the supergalactic plane tend to point toward center of the Virgo Cluster. This effects are greatest for "non-spirals" then for "spirals galaxies". Result for UGC/ESO and NGC (Tully) sample of galaxies are very similar. It should be remembered that detected perpendicularity of galaxy planes to the LSC plane can also be caused by the perpendicularity of galaxy planes to the vector to the LSC center "hedgehog model". The separate galaxy cluster belonging to the LSC was analyzed too. The anisotropy is observed but direction of the departure from isotropy are different in various groups.

The dependence of orientation on the morphological type is a curious phenomenon. Partially it is probably because we lose from analyses low face-on spirals. Because of shape of LSC most of them are galaxies with low absolute value δ_D and values η near 0 or Π, so observed anisotropy for that galaxies should be lowest. Within the framework of the tree main scenarios for origin of galaxies (primeval turbulence, hierarchical clustering and pancake model) our result (perpendicularity of galaxy planes to the LSC plane) excludes primeval turbulence and supports the pancake scenario. However it cannot be excluded that complicated structure of the LSC is due to a hybrid model or and to evolutionary effects.

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