АСТРОФИЗИКА

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ON THE ALIGNMENT OF GALAXIES IN CLUSTERS

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We explore the distribution of position angles (PA) of galaxies in clusters. We selected for study the isolated clusters, since the distribution of the galaxy orientation in clusters with close neighbors could be altered by the gravitational influence of the latter. We assume that galaxies are aligned, if their number at one 90° position angle interval is more than twice higher than at the other 90° interval. We study the galaxy PA distribution at the outer regions of clusters with smaller space density, where the probability of the PA variation in the result of interactions between galaxies is smaller than at the dense central regions. We found that the alignment of galaxies is more often observed in poor clusters and concluded that originally galaxies were aligned, but in the result of accretion in time of field galaxies with arbitrary orientations and also due to the mutual interactions the relative number of aligned galaxies decreases.

Keywords: *galaxies: clusters - galaxies: alignment - galaxies: large-sale structure*

1. *Introduction*. According to pancake scenario [1-3] galaxies form in the result of the gas-dust cloud collapse. At such case the position angles (PA) of galaxies will naturally be aligned independent on the cluster mass. According to Miller & Smith [4], Salvador-Sole & Solanes [5] Usami & Fujimoto [6], the galaxies could be aligned also at the hierarchical scenario of the cluster origin due to the cluster tidal field. At the latter scenario the galaxies will be aligned predominantly in rich clusters. Thus the alignment of galaxies in clusters is a clue for the explanation of their origin. Therefore a lot of efforts have been undertaken in the past for study the distribution of the PA of galaxies in clusters. Some evidence on the alignment of galaxies with the parent cluster were reported by Sastry [7], Adams, Strom & Strom [8], Carter & Metcalfe [9], Binggeli [10], Struble & Peebles [11], Rhee & Katgert [12], Lambas et al. [13], Flin & Olowin [14], Fong, Stevenson & Shanks [15]. More certainly the alignment was found between orientations of the cluster and of the BCG (cD) [7-9,16-22]. Plionis et al. [23] and Rong, Zhang & Liao [24] found evidence that significant galaxy alignment is present in dynamically young clusters. Meanwhile, Dekel [25], van Kampen & Rhee [26], Trevese, Cirimele & Flin [27], Djorgovski [28] and Cabanela & Aldering [29] found no galaxy alignment, except the alignment of the BCG with its parent cluster. Chen et al. [30] found a statistically significant galaxy-filament correlation, but not on the galaxy-cluster alignment. Thus, the

results on the study of the galaxy alignment in clusters were contradictory.

In this paper we undertook new search for alignment of galaxies and showed that galaxies are aligned mostly in poor clusters. We suggest that the primordial orientations of member galaxies were ordered at the cluster origin, but later on the assembly of field galaxies by the cluster and interactions between galaxies within the cluster introduce disorder in the galaxy orientations. We showed also that clusters in which the primordial alignment of galaxies preserved, do rotate.

2. *The data*. We study the possible alignment of galaxies in ACO [31] clusters. Many ACO clusters are themselves clustered [32-34]. The gravitational influence of the nearby cluster may affect on the orientation of galaxies in the studied cluster. In order to avoid this effect we studied isolated clusters. We compiled a list of 73 strongly isolated clusters with nearest neighbor located on sky at the projected distance >10 Mpc (Table 1). For comparison we studied also the clusters with smaller degree of isolation, with 5 to 9 Mpc projected distance

Table 1

THE LIST OF ISOLATED CLUSTERS WITH NEARBY NEIGHBOR AT PROJECTED DISTANCE >10 Mpc

Cluster	z	N_2	Cluster	z	N_2	Cluster	z	N_2
A595	0.0666	48	A1168	0.0906	41	A1825	0.0595	30
A602	0.0619	62	A1169	0.0586	79	A1827	0.0654	41
A634	0.0265	102	A1238	0.0733	68	A1849	0.0963	27
A635	0.0925	34	A1270	0.0692	63	A1864	0.0870	51
A660	0.0642	25	A1307	0.0817	67	A1890	0.0574	83
A671	0.0502	98	A1314	0.0335	119	A2018	0.0878	50
A690	0.0788	49	A1371	0.0398	61	A2019	0.0807	24
A692	0.0894	50	A1424	0.0768	72	A2022	0.0578	78
A695	0.0687	27	A1480	0.0734	31	A2048	0.0972	61
A699	0.0851	31	A1507	0.0604	57	A2082	0.0862	24
A724	0.0933	46	A1516	0.0769	60	A2107	0.0411	130
A727	0.0951	58	A1541	0.0893	79	A2108	0.0919	48
A744	0.0729	32	A1552	0.0858	74	A2110	0.0980	27
A757	0.0517	49	A1564	0.0792	52	A2122	0.0661	72
A779	0.0225	115	A1599	0.0855	25	A2142	0.0909	123
A819	0.0759	20	A1609	0.0891	27	A2148	0.0877	30
A834	0.0709	35	A1616	0.0833	48	A2162	0.0322	47
A858	0.0863	26	A1630	0.0648	36	A2178	0.0928	24
A1024	0.0734	49	A1684	0.0862	27	A2205	0.0876	39
A1028	0.0908	26	A1692	0.0842	49	A2255	0.0806	122
A1035	0.0684	59	A1750	0.0852	91	A2366	0.0529	53
A1066	0.0690	83	A1781	0.0618	45	A2593	0.0413	138
A1126	0.0646	33	A1783	0.0690	50	A2630	0.0667	37
A1139	0.0398	50	A1809	0.0791	94			
A1142	0.0349	64	A1812	0.0630	28			

to the nearest neighbor on sky. The list of the mild isolated 25 clusters is presented in Table 2. Redshifts of the selected clusters are $z < 0.1$ and they contain more than 20 galaxies within area with 2 Mpc radius. It is assumed that member galaxies of the most ACO clusters are located within 2 Mpc of the Abell radius [32], defined as $R_A = 1'.7/z$ ($H_0 = 72\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$) [35]. The member galaxies of clusters were retrieved from the SDSS-DR9 [36]. The galaxies with the primary mode (marked in the catalog as 1) and good quality of observations (marked by 3) were retrieved. According to [37] we retrieved galaxies with velocities within $\pm 1500\,\mathrm{km\,s^{-1}}$ of the cluster velocity. PAs are those at r band.

At the corresponding columns of Tables 1 and 2 the following information is given: the cluster designation, the redshift of the cluster and the number of galaxies in the cluster within 2 Mpc radius. The parameters of clusters are from NED[1].

Table 2

THE LIST OF MILD ISOLATED CLUSTERS WITH THE NEARBY NEIGHBOR AT PROJECTED DISTANCE $5 < d < 9$ Mpc

Cluster	z	N_2	Cluster	z	N_2	Cluster	z	N_2
A912	0.0446	21	A1589	0.0725	100	A1983	0.0436	149
A933	0.0956	47	A1638	0.0620	33	A1991	0.0587	99
A1100	0.0463	53	A1650	0.0838	59	A2029	0.0773	77
A1149	0.0710	37	A1663	0.0843	60	A2065	0.0726	115
A1185	0.0325	182	A1691	0.0721	75	A2089	0.0711	60
A1205	0.0754	46	A1775	0.0717	60	A2092	0.0669	50
A1267	0.0329	28	A1795	0.0625	103	A2149	0.0679	40
A1291	0.0527	84	A1831	0.0615	37			
A1468	0.0844	31	A1927	0.0945	35			

3. *Analysis*. We used a simple method for search of the alignment of the orientation of galaxies in clusters. We divided the range of PAs of galaxies in each cluster into two 90° sections so that to have a high number N_h of galaxies at one section and a small number N_s of galaxies at the other section. We assume that there is an alignment signal, if the number of galaxies at one 90° section is by at least 2 times higher than at the other 90° section.

A primordial galaxy alignment in clusters could be severely damped by the violent relaxation, by the exchange of angular momentum in galaxy interactions over a Hubble time [38] that mostly occur in the dense cluster environment. Therefore, we first searched the orientation of galaxies in the outer area of clusters

[1] *The NASA/IPAC Extragalactic Database (NED) is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.*

Table 3

THE LIST OF STRONGLY ISOLATED CLUSTERS WITH THE ALIGHNMENT SIGNAL FOR GALAXIES AT THE RING WITH RADII $1 \div 2$ Mpc

Cluster	I_{PA}	N_h	N_s	$(N_h / N_s)_{1\div2}$
A595	37-122	12	3	4.0
A635A	78-165	8	2	4.0
A660A	160-69	12	4	2.2
A695A	26-107	9	3	3.0
A699A	82-158	12	6	2.0
A724	171-81	14	3	4.7
A744A	2-86	7	3	2.3
A819A	23-113	7	3	2.3
A834	18-106	15	4	3.75
A858	56-136	8	2	4.0
A1028A	1-89	9	4	2.25
A1035A	69-158	8	4	2.0
A1126A	18-108	11	5	2.2
A1139	6-96	12	6	2.0
A1168	3-84	12	5	2.4
A1169	20-108	23	8	2.9
A1238A	102-10	23	7	3.3
A1270	69-159	17	7	2.4
A1307	164-74	24	11	2.2
A1371	39-121	18	7	2.6
A1480A	161-70	11	5	2.2
A1516A	76-160	18	8	2.25
A1541	64-144	25	7	3.6
A1552	131-41	24	12	2.0
A1599A	100-3	7	3	2.3
A1616A	2-89	16	6	2.7
A1684A	68-156	8	4	2.0
A1781A	68-156	19	7	2.7
A1783A	88-167	12	3	4.0
A1809A	15-103	24	12	2.0
A1812A	32-122	12	4	3.0
A1825A	115-20	11	5	2.2
A1849A	73-150	9	2	4.5
A2018A	44-131	21	7	2.6
A2019A	75-156	9	4	2.25
A2082A	144-40	11	1	11.0
A2108	32-108	12	3	4
A2110	91-180	11	3	3.7
A2122A	51-141	22	11	2.0
A2148	108-18	8	3	2.3
A2178A	51-133	9	4	2.25
A2366A	85-170	9	4	2.25
A2630A	44-132	10	2	5

at the ring with cluster-centric radii $1 \div 2$ Mpc.

The results of counts in the outer ring of clusters with a smaller degree of isolation is presented in Table 3. In the corresponding columns of Table 3 the following information is given: 1st - the cluster designation; 2d - the interval of PAs at which the high number of galaxies are distributed; 3d - the number N_h of galaxies at this section; 4th - the number of galaxies at the opposite section; 5th - the ratio N_h / N_s at the searched region. In these clusters the alignment signal was found only for 8 out of 26 clusters, 32%.

Table 4

THE LIST OF THE MILD ISOLATED CLUSTERS WITH THE ALIGHNMENT SIGNAL FOR GALAXIES AT THE RING WITH RADII $1 \div 2$ Mpc

Cluster	I_{PA}	N_h	N_s	$(N_h / N_s)_{1 \div 2}$
A933	24-111	18	8	2.25
A1100	83-180	15	7	2.1
A1119	63-157	8	4	2.0
A1205	96-171	8	4	2.0
A1267	43-140	13	4	3.25
A1468	124-6	9	4	2.25
A1775	45-132	37	17	2.2
A1927	57-141	17	4	4.25
A2149	16-104	12	4	3.0

At the ring with cluster-centric radii $1 \div 2$ Mpc 43 clusters out of 73, i.e 59% have alignment signal (Table 3). Note that in the case of a random distribution of PAs the numbers of galaxies in two 90° intervals could occasionally differ from each other by more than 2 times. In order to verify whether the found number of clusters with alignment signal are real or are a result of random distribution of the galaxy PAs we applied non-parametric bootstrapping statistical test making 1000 simulations. The same statistical test was applied below for checking the reality of the found alignments in other cluster samples.

The probability that in 43 clusters out of 73 the ratio N_h / N_s exceeds 2 is real and is not a result of random distribution is 58.90% of success and a 95 percent confidence interval from 46.76% to 70.29% with a p-value = 0.01597. The p-value or probability value (>0.05) is the probability of obtaining test results at least as extreme, as the results actually observed during the test, assuming that the null hypothesis is correct. Hence, the probability that the found galaxy alignments at rings are real, is sufficiently high.

The orientations of 19 clusters with an alignment signal studied in this paper were determined by Plionis [19]. In Fig.1 the distribution of PAs of galaxies in these clusters and the PAs of the cluster large axis determined by Plionis [19] are shown. The PAs of the large axes of 14 clusters are within an interval of

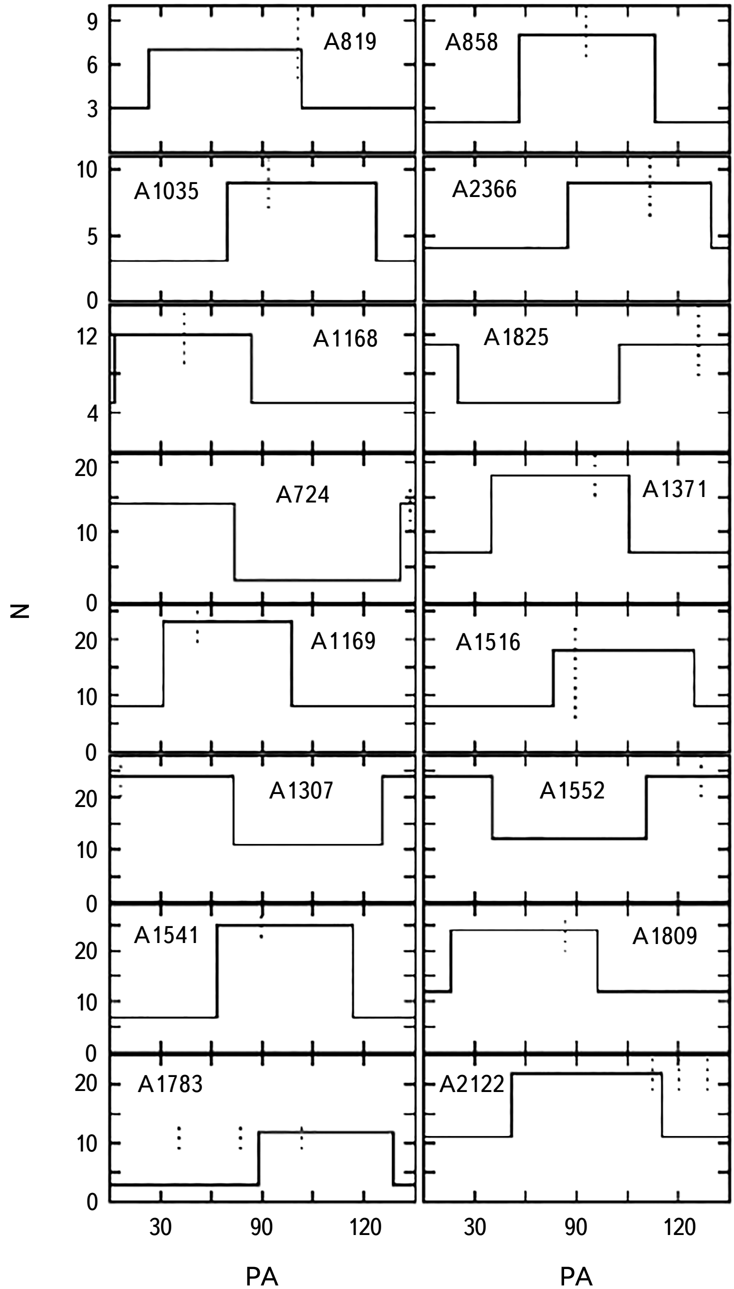

Fig.1. The comparison of the distribution of PAs of galaxies in clusters with the alignment signal with the cluster PA from Plionis [19] shown by dotted line. In cases of A1783 and A2122 the interval of the errors of the PA of the large axes of the cluster are also shown.

PAs of aligned galaxies. For 2 clusters, A1783 and A1812, the PA of their large axes fall into the interval of PAs of aligned galaxies, if to take into account the errors of the PA measurements [19] about 30°. The PAs of large axes of only 3 clusters, A1126, A1139, and A1812 are out of the 90° interval of the PAs of galaxies with alignment signal. The probability of 16 chance coincidences out of 19 is sufficiently small, 0.01. Even with the exclusion of A1783 and A1812, the probability of the chance coincidences of 14 out of 19 is still small, 0.02. The coincidence of the cluster large axes orientation with the interval of PAs of the majority of the cluster galaxies shows that the applied simple method for searching the alignment of galaxies in clusters is reliable.

The results of counts in the outer ring of clusters with a smaller degree of isolation and at the central area of strongly isolated clusters are presented respectively in Table 4 and Table 5 identical to Table 3.

In the outer ring of clusters with a smaller degree of isolation the alignment signal is found only for 8 out of 25 clusters, 32%. The probability that the found alignment signal in the ring of 8 out of 25 clusters is real, is 32.00% of success with a 95 percent confidence interval from 14.94% to 53.50% with a p-value = 0.01078.

At the central region of strongly isolated clusters the alignment signal is found for 27 clusters, 36%, out of the studied 73. The probability that the alignment at the central area of clusters does not occur by chance and is real is 36.98% of success with the 95 percent confidence interval from 25.97% to 49.08% and p-value = 0.01442. Hence, the found alignment of galaxies in both cluster samples are caused rather by random distribution of the galaxy PAs and are not real.

3.1. *The dependence of the alignment on the cluster richness.* The alignment of galaxies could depend on the richness of clusters and/or on the absolute magnitude of the observed galaxies, i.e. on the cluster redshift. In order to find out whether the alignment signal depends on the cluster richness or distance we split the list of 73 strongly isolated clusters into two parts: with low and high redshift clusters, and also poor and rich ones. In the consecutive lanes of Table 6 the average redshift z, the average number N_2 of galaxies, the minimal absolute magnitude $<M_r>$ in r-band for the average redshift, the number N_{as} of galaxies with alignment signal and the ratio N_{as}/N_t of the number of clusters with alignment signal to the total number of clusters are presented for nearby (column 2) and distant (column 3) clusters. In Table 7 the same data are presented for samples of rich and poor clusters.

Table 6 shows that difference between relative numbers of galaxies with alignment signal in nearby and distant clusters is not high, although the distant clusters are on average by 1.5 times farther and the limiting absolute M_r magnitudes of galaxies in this clusters differ by about 1^m. The average total

Table 5

THE LIST OF CLUSTERS WITH ALIGNED GALAXIES AT THE CLUSTER CENTRAL REGION

Cluster	I_{PA}	N_h	N_s	$(N_h / N_s)_{1\div 2}$
A595	37-122	12	3	2.1
A660A	160-69	12	4	2.0
A695A	26-107	9	3	2.7
A727	16-106	22	17	2.8
A744A	2-86	7	3	4.5
A834	18-106	15	4	3.0
A1028A	1-89	9	4	2.25
A1126A	18-108	11	5	3.0
A1168	3-84	12	5	2.7
A1238A	102-10	23	7	2.75
A1371	39-121	18	7	2.0
A1541	64-144	25	7	2.5
A1552	131-41	24	12	2.2
A1564A	32-122	13	12	2.25
A1599A	100-3	7	3	2.0
A1616A	2-89	16	6	2.7
A1630A	7-96	7	4	2.6
A1692	9-96	17	9	3.0
A1750A	13-103	36	23	2.7
A1781A	68-156	19	7	2.1
A1812A	32-122	12	4	3.0
A2019A	75-156	9	4	2.7
A2048	0-90	19	14	2.1
A2082A	144-40	11	1	3.0
A2108	32-108	12	3	3.1
A2122A	51-141	22	11	2.2
A2205A	46-136	14	10	2.0

numbers of galaxies in clusters of both samples also do not differ from each other significantly. The relative number of nearby clusters with the alignment signal is 0.51 with 50.06% of success and 95 percent confidence interval from 38.71% to

Table 6

THE PARAMETERS OF THE NEARBY AND DISTANT CLUSTERS

	Nearby clusters	Distant clusters
$<z>$	0.0565 ± 0.0143	0.0860 ± 0.0066
$<N_2>$	62 ± 30	50 ± 26
$<M_r>$	-19.09	-20.02
N_{as}	19	24
N_{as}/N_t	0.51 ± 0.12	0.65 ± 0.13

Table 7

THE PARAMETERS OF POOR AND RICH CLUSTERS

	Rich clusters	Poor clusters
z	0.0655 ± 0.0207	0.0774 ± 0.0143
$<N_2>$	77 ± 25	35 ± 9
$<M_r>$	-19.47	-19.78
N_{as}	15	28
N_{as}/N_t	0.40 ± 0.10	0.76 ± 0.14

62.59% with a p-value = 3.182e-03. The relative number of distant clusters with the alignment signal is 0.65, with 64.38% of success and a 95 percent confidence interval from 52.30% to 75.25% with a p-value = 1.818e-04.

The situation is different when we compare rich and poor clusters. Table 7 shows that the differences between the average redshifts and the limiting absolute magnitudes M_r of these two samples are smaller in comparison to those in nearby and distant clusters. However, the relative number of poor clusters with the alignment signal is by about 2.6 times higher in comparison to rich ones. The relative number of rich clusters with the alignment signal is 0.40 with 39.72% of success and a 95 percent confidence interval from 28.45% to 51.85% with a p-value = 1.173e-02. The relative number of poor clusters with the alignment signal is 0.76 with 75.34% of success and a 95 percent confidence interval from 63.85% to 84.68% with a p-value = 1.514e-15. Thus, in poor clusters the probability of the reality of the found alignment is sufficiently high, about 80%.

4. *Discussion and conclusions*. By study of the distribution of PAs of galaxies in the ring with radii $1 \div 2$ Mps of 73 strongly isolated clusters the alignment signal is found in 43 clusters, i.e. in about 60%. Such high number of clusters with aligned galaxies may not be caused by a chance distribution of the galaxy PAs. Among the less isolated clusters and in the central dense area of clusters with 1 Mpc radius the alignment signal is found respectively in about 37% and 29% of clusters, that is close to the expected number of a chance occurrence of the alignment signal, the ratio $N_h/N_s > 2$. The separate analysis of clusters of different richnesses and distances showed that the alignment depends on the cluster richness. Alignment is found in about 75% of poor clusters with on average 35 galaxies within 2 Mpc. The probability that this is not due by a random distribution of the galaxy PAs is sufficiently high. This evidences in favor of the pancake scenario [1,2] of the cluster formation. If so, clusters could preserve the angular momentum of the primordial gas cloud.

According to Miller & Smith [4], Salvador-Sole & Solanes [5] Usami & Fujimoto [6], the galaxies could as well be aligned in the hierarchical scenario due to the tidal field of the cluster. However, the tidal field of the cluster would apparently be more effective in rich clusters with higher mass and the alignment would be observed in rich clusters. Whereas, we found the opposite.

During the cluster evolution the primordial alignment of galaxies could be altered. The alignment rate will decrease in the result the gravitational influence of nearby clusters and mutual interactions between galaxies. Apparently the rate of interactions is higher in rich clusters and especially at the cluster dense central regions. The gravitational influence would apparently have a smaller effect on the orientation of massive galaxies. Therefore, the alignment of only very massive BCGs (cDs) has been found with the cluster orientation [7-10,17-22]. The inclusion to the cluster content the faint field galaxies by the hierarchical assembly ([39] and references therein) with arbitrary orientations will certainly decrease the relative number of aligned galaxies. The poorer is the cluster, i.e. the less massive it is, the smaller amount of field galaxies would be assembled. Thus, the primordial alignment is better preserved in poor clusters, in which both reasons for altering it, interactions between galaxies and assembly of the field galaxies, are less effective.

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О НАПРАВЛЕННОСТИ ГАЛАКТИК В СКОПЛЕНИЯХ

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В работе приводятся исследование распределения позиционных углов галактик в скоплениях. Были отобраны изолированные галактики, поскольку ориентации галактик в скоплениях с близкими соседями будут изменены из-за гравитационного воздействия последних. Предпологается, что галактики имеют общую направленность, если их количество в одном 90-градусном интервале более двух раз превышает их количество в другом 90-градусном интервале. Проведены исследования распределения позиционных углов галактик во внешних областях скоплений, где вероятность изменения позиционных углов в результате взаимодействия с другими галактиками меньше, чем в более плотных центральных областях. Обнаружено, что направленность галактик чаще наблюдается в бедных скоплениях, что галактики первоначально имели общую направленность, однако с течением времени в результате аккреции галактик поля с произвольными ориентациями, а также из-за взаимного воздействия с другими галактиками, количество галактик, имеющих общую направленность, уменьшается.

Ключевые слова: *галактики:скопления - галактики:направленность - галактики*

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