АСТРОФИЗИКА

ТОМ 63 ФЕВРАЛЬ, 2020 ВЫПУСК 1

ON THE SIZE AND THE MASS OF GALAXY CLUSTERS

H.M.TOVMASSIAN

Received 21 July 2019
Accepted 18 December 2019

We counted galaxies in the area with 10 Mpc radius around 30 isolated ACO clusters at redshifts $z < 0.1$. We show that surface densities of galaxies around clusters regularly decrease till 10 Mpc. Separate counts of blue and red galaxies of the cluster environment revealed that at all cluster-centric distances the surface density of red galaxies are higher than that of blue ones. The surface density of red galaxies decrease significantly with increase of distance from the cluster. Meanwhile, the decrease of the surface density of blue galaxies is very smooth and is almost not noticeable at higher cluster-centric distances. It is suggested that the red population of the cluster environment consists of backsplash galaxies that form the cluster halo, which is extended farther than 10 Mpc from the cluster center. The blue population consists mainly from the field galaxies. The velocity dispersion of blue galaxies in the cluster environment is higher of the velocity dispersion of red galaxies that evidences on their different entity. The mass of the halo is comparable to the cluster mass.

Keywords: *galaxies: clusters*

1. *Introduction*. Galaxy clusters are the largest objects in the Universe, comprising hundreds to thousands galaxies. According to the hierarchical structure formation paradigm [1-4], galaxy clusters grow by the continuous accretion of smaller galaxy groups and individual galaxies. Member galaxies of the most ACO [5] clusters are located within 2 Mpc of the Abell radius [6], defined as $R_A = 1'.7/z$ ($H_0 = 72\,\mathrm{km\,s^{-1}}$) [7], where z is the cluster redshift. However, the diameters of a few nearby clusters are larger. The diameter of the Coma cluster was traced till at least 10 Mpc [8,9]. The accreted galaxies around a cluster form its faint extension. The resulting gravitation force of the cluster would be higher of the determined by galaxies confined in the volume of the proper cluster. In this paper we counted galaxies in the environment of 30 ACO clusters up to 10 Mpc from their centers and estimated the average size of the cluster halo and mass.

2. *The selection of isolated clusters and counts of galaxies*. It is known that many Abell clusters are themselves clustered [6,10,11]. We selected for study the isolated clusters. The velocity dispersion of galaxies in clusters are in the range of about 800 to 1500 $\mathrm{km\,s^{-1}}$ [12]. We assumed the cluster is isolated, if the nearest neighbor ACO cluster with velocity that differs from that of the

sample cluster by less than 3000 km s^{-1}, is located at the projected distance >15 Mpc on the sky. If the difference of radial velocities is > 3000 km s^{-1}, the neighbor cluster could be nearer to the sample cluster on sky. The ACO clusters at redshifts < 0.1 and containing at least 50 galaxies within 2 Mpc are selected for the study. Only the clusters, the circular area around which with radius 10 Mpc was completely covered by SDSS-DR9 [13], are included in the study. Finally the list of 30 ACO clusters were compiled.

The galaxies of the SDSS-DR9 catalog in the area with the 2 Mpc assumed radius of each cluster and in the consecutive rings with cluster-centric radii 2-4, 4-6, 6-8 and 8-10 Mpc were counted. The areas at which the counts were made are further labelled as A, B, C, D and F. The SDSS uniformly covers the studied

Table 1

THE LIST OF ISOLATED CLUSTERS

Cluster	z	D	N_A	N_B	N_C	N_D	N_F
A671	0.0502	34.2	95	51	38	47	58
A757	0.0517	25.7	50	28	22	16	37
A1024	0.0734	15.8	51	43	28	27	41
A1035	0.0680	14.6	57	27	26	42	29
A1066	0.0686	26.7	58	59	48	65	52
A1100	0.0463	19.5	54	32	62	56	69
A1139	0.0393	20.7	91	45	58	95	85
A1142	0.0349	16.9	66	70	64	66	73
A1169	0.0586	24.5	79	38	33	38	36
A1307	0.0817	14.5	69	57	63	71	55
A1314	0.0335	24.4	115	24	72	48	71
A1507	0.0604	20.3	58	43	39	53	44
A1541	0.0839	16.1	78	41	35	39	39
A1552	0.0858	16.1	78	64	31	47	40
A1564	0.0792	19.3	55	26	27	41	60
A1616	0.0834	25.6	48	40	31	24	25
A1749	0.0573	15.8	56	60	87	59	69
A1750	0.0852	17.9	95	65	44	73	65
A1808	0.0624	26.2	60	35	34	34	31
A1864	0.0879	23.9	54	38	45	65	62
A1890	0.0575	25.4	83	35	26	36	35
A1983	0.0436	21.8	153	57	54	95	81
A2018	0.0878	41.2	51	42	39	25	27
A2107	0.0414	20.0	134	64	44	57	65
A2108	0.0903	25.8	51	42	39	25	27
A2122	0.0661	24.6	74	44	65	68	52
A2162	0.0332	18.2	50	39	68	117	80
A2169	0.0578	18.8	71	40	89	82	49
A2255	0.0780	29.1	124	62	58	65	63
A2593	0.0424	31.0	143	119	25	17	35

area, producing a homogeneous data-set. Since we study the distribution of galaxies in the cluster environment, where surface density of galaxies is small, the problem of the "fiber collisions", that is characteristic to SDSS, is not relevant. The galaxies mentioned in SDSS as "primary sources" were selected. The selected galaxies are within the same velocity limits ($\pm 1500\,\mathrm{km\,s^{-1}}$) of the cluster velocity, as galaxies of the proper cluster within 2 Mpc radius. The list of the selected isolated clusters and the results of counts are presented in Table 1. In the consecutive columns of Table 1 the following data is presented: 1 - the cluster ID, 2 - the redshift *z*, 3 - the projected distance *D* in Mpc from the sample cluster to the nearest ACO neighbor, 4-8 - the numbers N of galaxies in the corresponding bins.

2.1. *The results and discussion*. The sums of counts in the A to F areas for all 30 clusters are presented in the 1st raw of Table 2. Using the results of counts we determined overdensities by the formula $(N_i/N_{last} \times S_{last}/S_i) - 1$ and the corresponding errors according to $\sigma = \left[(S_{last}/S_i)\sqrt{(N_i(1 + N_i/N_{last}))}\right] \Big/ N_{last}$. The determined ovedensities and corresponding errors are presented in the 2nd raw of Table 2. The averaged for one cluster surface densities of galaxies ρ per Mpc^2 and corresponding errors in the cluster region and in the surrounding rings are presented in the 3rd raw. The errors are determined as $\sqrt{N}/S$, where S is the surface in Mpc^2 of the corresponding area. In Fig.1 the dependence of surface densities ρ on the cluster-centric distance is shown.

Table 2

THE TOTAL NUMBERS OF GALAXIES, OVERDENSITIES AND SURFACE DENSITIES ρ WITH CORRESPONDING ERRORS AT THE MAIN BODY OF CLUSTERS WITH RADIUS 2 Mpc AND AT DIFFERENT CLUSTER-CENTRIC RINGS

	N_A	N_B	N_C	N_D	N_F
N_t	2302	1403	1381	1570	1551
Overdens	12.3 ± 0.87	2.71 ± 0.19	1.60 ± 0.16	1.30 ± 0.12	0.0 ± 0.09
ρ	6.1 ± 0.13	1.2 ± 0.033	0.73 ± 0.02	0.59 ± 0.015	0.46 ± 0.012

Table 2 shows that overdensities of galaxies regularly decrease with increase of the cluster-centric distance. Fig.1 shows the decrease of the surface densities ρ of galaxies with cluster-centric distance. The regular decrease of the surface density with cluster-centric distance shows that galaxies of the cluster environment till about 10 Mpc are associated with the cluster. The increase of ρ towards cluster could apparently be due either to the faint extension of the proper cluster or to the field galaxies assembled by the cluster gravitation. Both these galaxies form the halo of the cluster. Apparently, the mass of the halo should be taken into account for estimation of the cluster gravitation.

In order to find out whether the galaxies in the environment of clusters represent a faint extension of clusters or are the field galaxies physically unrelated to them, we considered separately the blue (spirals and irregulars) and the red (presumably elliptical) galaxy population at the cluster environment.

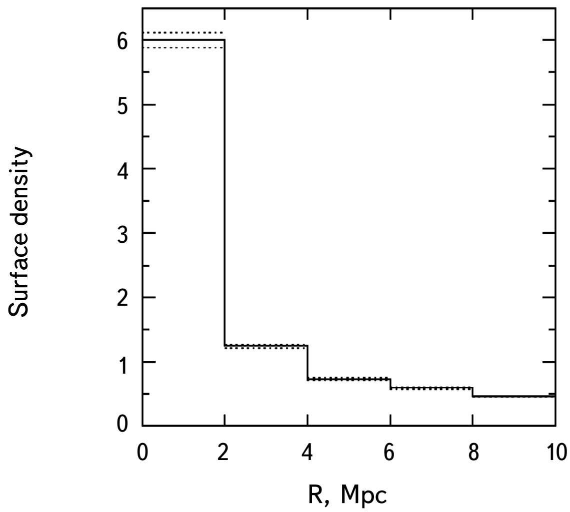

Fig.1. The averaged for one cluster surface densities per 1 Mpc^2 of galaxies in the cluster area A with 2 Mpc radius and in the rings B, C, D and F surrounding it. The errors are shown by dotted lines.

It is known that early-type red galaxies compose the main population of clusters [14-21], while the late-type blue galaxies dominate in the field [14,22-25]. Galaxy clusters are located in filaments, which contain larger blue population in comparison to clusters [26]. For differentiation between blue and red galaxies we determined their colors $u-g$ and $g-r$ using the photometric data, marked in the SDSS-9 as "clean photometry", and applied the diagnostic diagram of Strateva et al. [27]. The galactic absorption was corrected according to NED. We determined

Table 3

THE NUMBERS N_b AND N_r OF BLUE AND RED GALAXIES IN RINGS B, C, D AND F AROUND CLUSTERS AND THE AVERAGED FOR ONE CLUSTER SURFACE DENSITIES PER Mpc^2 WITH ERRORS

Area	N_b	N_r	$\rho_b \pm \sigma$	$\rho_r \pm \sigma$
B	433	755	0.38 ± 0.02	0.67 ± 0.02
C	510	606	0.27 ± 0.01	0.53 ± 0.01
D	563	701	0.21 ± 0.01	0.26 ± 0.01
F	593	645	0.17 ± 0.007	0.19 ± 0.007

the number of blue and red galaxies in the rings *B* to *F*. The results are presented in Table 3, in the corresponding columns of which the following data is given: 1st column - the area; 2nd and 3rd columns - the numbers N_b and N_r of blue and red galaxies respectively; columns 4 and 5 - the averaged for one cluster surface densities ρ per Mpc^2 of the blue and the red galaxies respectively with corresponding errors σ.

The dependences of the surface densities of blue and red galaxies in rings at different cluster-centric distances are presented in Fig.2. Table 3 and Fig.2 show that the surface density of red galaxies in all rings from B to F is sufficiently higher than that of blue galaxies. For the unrelated to cluster field galaxies, the contrary would be observed. The red galaxies in the cluster environment apparently are the backsplash galaxies, which have crossed the cluster core at least once and are observed on the other side of its periphery [19,28-33]. It is noteworthy that the decrease of the surface density of red galaxies with cluster-centric distance is sufficiently sharp and is smoother for blue ones.

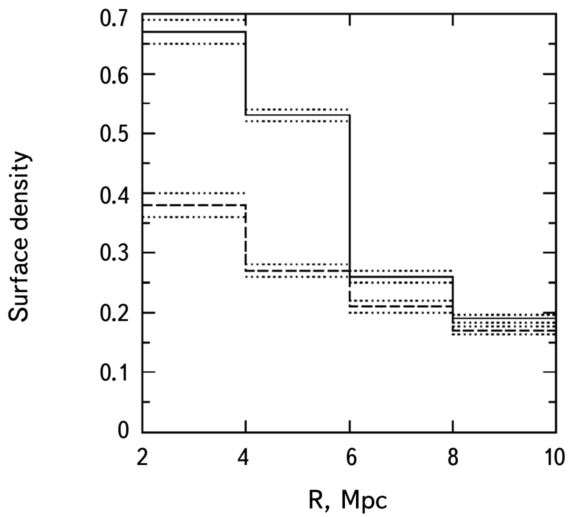

Fig.2. The averaged for one cluster surface densities of blue and red galaxies in rings B, C, D and F. The surface densities of red galaxies are shown by solid lines, while that of blue galaxies - by dashed lines. Errors are shown by dotted lines.

The surface density of blue galaxies decreases insignificantly from ring C to F. It means that the observed blue galaxies at cluster-centric distances >4 Mpc are mostly the field objects projected over the area surrounding the cluster.

2.2. *Velocity dispersions of blue and red galaxies*. If blue and red galaxies in the cluster environments indeed have different origin, their dynamical properties could differ from each other. The velocity dispersion of red galaxies being the members of a confined dynamical system could be smaller than that of the field galaxies with higher diversity of velocities. We determined the velocity dispersions σ_v of both types of galaxies located at cluster-centric distances from 4 to 10 Mpc. The results are presented in Table 4. In the 2nd and 4th columns of Table 4 the numbers N_b and N_r of respectively blue and red galaxies in the ring with radii 4 and 10 Mpc around each cluster is presented. In columns 3 and 5 the corresponding velocity dispersions are presented. The column 6 shows the difference $=\sigma_b - \sigma_r$ is shown.

Table 4 shows that the velocity dispersion of blue galaxies in the environment of 28 out of 30 clusters is higher than the velocity dispersion of red galaxies.

Table 4

THE VELOCITY DISPERSIONS OF BLUE AND RED GALAXIES

Cluster	N_b	σ_b km s^{-1}	N_r	σ km s^{-1}	Δ km s^{-1}
A671	40	688	56	558	130
A757	24	636	25	452	184
A1024	21	568	37	532	36
A1035	34	878	42	781	97
A1066	43	783	79	706	77
A1100	71	716	61	586	130
A1139	68	723	74	622	101
A1142	74	761	58	645	116
A1169	808	38	760	48	48
A1307	34	704	95	444	260
A1314	90	580	45	515	65
A1507	55	994	79	989	5
A1541	39	691	69	759	-68
A1552	37	648	56	508	140
A1564	33	663	57	594	69
A1616	19	786	34	555	231
A1749	72	841	93	760	81
A1750	30	617	123	470	147
A1808	41	633	36	591	42
A1864	36	844	98	773	71
A1890	42	447	31	378	69
A1983	99	820	90	823	-3
A2018	28	625	52	565	60
A2107	52	744	49	743	1
A2108	13	674	24	356	318
A2122	46	712	98	579	133
A2162	101	500	59	451	49
A2169	60	710	91	653	57
A2255	52	607	99	531	76
A2593	17	515	38	315	200

According to the Bernulli formula the probability that the velocity dispersion of blue galaxies in the environment of clusters is higher than that of red galaxies by chance, is less than 10^{-6}. Thus, the difference between velocity dispersions of blue and red galaxies in the cluster environment support the conclusion on their different entity.

3. *Conclusions*. We counted the SDSS-DR9 galaxies in the area of 30 isolated clusters within 2 Mpc and in 4 rings around clusters with 2 Mpc width each till 10 Mpc. The galaxies with velocities within $\pm 1500\,\mathrm{km\,s^{-1}}$ of the cluster velocity were counted. The overdensities show a certain decrease of the number of galaxies in the cluster environment with the cluster-centric distance of the ring. The separate consideration of the distribution of blue and red galaxies allows to suggest that the decrease of the surface density with cluster-centric distance is due mainly to the backsplash red galaxies. Hence, the red population of the cluster environment is physically associated with it forming its faint halo. Meanwhile, the majority of the observed blue population in the cluster environment consists mainly of the unrelated to cluster field galaxies. The higher velocity dispersion of blue galaxies in the cluster environment in comparison to that of red galaxies confirms that they are field object with large variety of velocities. The small increase of the surface densities of blue galaxies at small cluster-centric distances is apparently due to infalling galaxies. Thus, we suggest that the halo mass is determined mainly by the red galaxies. Red galaxies were not found before at such high distances from the cluster. The radius of the red halo could be higher than 10 Mpc, since at this cluster-centric distance the decrease of the surface density of red galaxies is not terminated.

The number of the observed 2700 red galaxies in the environment of 30 clusters is higher of the number of galaxies within clusters with 2 Mpc radius, 2300. It follows that the baryon mass of the cluster together with its halo is about twice higher than the assumed cluster mass.

Acknowledgements. This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

377, W. California 30, Glendale, CA,
USA, e-mail: htovmas@gmail.com

О РАЗМЕРАХ И МАССАХ СКОПЛЕНИЙ ГАЛАКТИК

Г.М.ТОВМАСЯН

Проведен подсчет галактик в области с радиусом 10 Мпк вокруг 30 изолированных АСО скоплений с красными смещениями <0.1. Показано, что поверхностные плотности галактик вокруг скоплений регулярно уменьшаются до расстояний 10 Мпк. Раздельные подсчеты голубых и красных галактик в окрестностях скоплений показали, что поверхностные плотности красных галактик больше поверхностных плотностей голубых галактик на всех расстояниях от скопления. Поверхностные плотности красных галактик резко уменьшаются с расстоянием от центра скопления, тогда как уменьшение поверхностных плотностей голубых галактик очень плавное и почти незаметно на больших угловых расстояниях от скопления. Предполагается, что популяция красных галактик в окрестностях скопления состоит из галактик, которые попав в скопление прошли через него и и затем удалились от него. Эти галактики составляют гало скопления, которое простирается далее 10 Мпк от центра скопления. Популяция голубых галактик состоит преимущественно из галактик поля. Масса гало больше, чем масса самого скопления.

Ключевые слова: *галактики: скопения*

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