

The splashback radius of groups and clusters of galaxies at low redshifts

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We present a study of the distribution of galaxies along the radius of 157 groups and clusters of galaxies ($200 \text{ km s}^{-1} < \sigma < 1100 \text{ km s}^{-1}$) of the local Universe ($0.01 < z < 0.1$). We introduced a new boundary of galaxy systems and identified it with the splashback radius R_{sp} . We also identified the central region of galaxy systems with a radius of R_c . These radii are defined by the observed integral distribution of the total number of galaxies depending on the squared distance from the center of the groups/clusters coinciding, as a rule, with the brightest galaxy. We show that the radius R_{sp} is proportional to the R_{200c} (radius of the virialized region of a galaxy cluster) and to the radius of the central region R_c with a slope close to 1. Among the obtained dependences of the radii on X-ray luminosity, the $\log R_{sp} - \log L_X$ relation has the lowest scatter. We measured $\langle R_{sp} \rangle = 1.67 \pm 0.05 \text{ Mpc}$ for the total sample, $\langle R_{sp} \rangle = 1.14 \pm 0.14 \text{ Mpc}$ for galaxy groups with $\sigma \leq 400 \text{ km s}^{-1}$, $\langle R_{sp} \rangle = 2.00 \pm 0.20 \text{ Mpc}$ for galaxy clusters with $\sigma > 400 \text{ km s}^{-1}$. We found the average ratio of the radii $R_{sp}/R_{200c} = 1.40 \pm 0.02$ or $R_{sp}/R_{200m} = 0.88 \pm 0.02$.

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1. Introduction

Clusters of galaxies are the largest gravitationally bound objects in the Universe. They are collapsing structures known as dark matter halos. Clusters of galaxies are continuously increasing in mass both as a result of the merging with individual galaxies and smaller groups of galaxies, and as a result of continuous infall of dark matter from the environment. Clusters of galaxies do not have clear boundaries, which are often determined by density contrast relative to the critical or average density of the universe. Their evolution is considered within the framework of the spherical collapse model in the expanding universe (e.g. [1, 2]).

Using N-body simulations of the motion of particles of a dark matter halo (galaxies), it was found that a significant part of them (up to 50%) located outside the virialized regions of galaxy clusters (up to $2R_{vir}$ or $2R_{200}$) have already been inside [3–5].

[6] presents the results of Millennium simulations for 75 galaxy clusters ($z = 0.0$), where it is shown that a significant part of the galaxies bounce up to $3r_{proj}/r_{200}$ in the phase-space diagram.

The radius of galaxy clusters (physical halo boundary), the splashback radius R_{sp} , was introduced in [7] as the radius at which newly accreted dark matter particles are piled up within the apocenters of their orbits. The R_{sp} radius is clearly visible on the dark matter halo density profiles as a sharp density drop [7, 8]. In simulations performed in [9], it is shown that the localization of R_{sp} depends on the rate of mass accretion into the cluster: in the halo with a rapid accretion rate $R_{sp} \approx 0.8 - 1R_{200m}$, in the halo with a slow rate — $\sim 1.5R_{200m}$.

In this work, we are looking for observational manifestations of splashback features in a sample of groups and clusters of galaxies (data from the SDSS catalog). In [10] we show the edge of the galaxy clusters, clearly identified by the integral distribution of the number of all galaxies in a cluster depending on the squared clustercentric distance, which we call the radius of the halo, R_h . This radius is usually larger than the radius R_{200c} and is measured along the projected profile when a sharp increase in the number of galaxies in the center of clusters ends. We identified them later with the splashback radius R_{sp} and gave the results of its measurements for ~ 100 groups/clusters of galaxies [10–13]. In the works [12, 13] we have shown that the distribution of early-type galaxies in clusters allows for a more accurate estimate of the desired radius. We have measured for 40 galaxy systems the average radius $\langle R_{sp} \rangle = 1.54 \pm 0.06 R_{200c}$ or $R_{sp} = 0.96 \pm 0.06 R_{200m}$ (if we take into account $4R_{200c} \approx 2.5R_{200m}$), which varies from 1.10 Mpc for the group NGC 5627 with $\sigma = 314 \text{ km s}^{-1}$ to 4.17 Mpc for the cluster Coma (A 1656) with $\sigma = 921 \text{ km s}^{-1}$. Here R_{200c} (hereinafter R_{200}) is the radius of a cluster inside which the density exceeds the critical density of the universe by a factor 200. This radius in our works is determined by the dispersion of radial velocities of galaxies in the systems. In model simulations, the R_{200m} radius is often used, within which the density in the system exceeds the average density of the universe by a factor 200.

In this study, we used a sample of 157 groups/clusters of galaxies from the regions of superclusters of galaxies Leo (N=12), Hercules (N=27), Ursa Major (N=19), Corona Borealis (N=8), Bootes (N=13), from other smaller superclusters (N=11) and fields (N=20), groups of galaxies from the region of the A 1656/ A1367 supercluster (N=48). For these systems of galaxies we have determined radii R_{sp} (splashback radius) and R_c (core radius) from the observed profile and found the dependences of the radii on other galaxy cluster characteristics. This study uses the data of the SDSS (Sloan Digital Sky Survey Data Releases 7, 8) and 2MASS XSC (Two-Micron ALL-Sky

Survey Extended Source Catalog) catalogs and NED (NASA Extragalactic Database). Throughout this study we adopted the following values of cosmological parameters: $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

2. Method and data

In the papers [10, 11, 13, 14] we presented the dynamical characteristics for a region with a radius of R_{200} for almost the entire sample of groups and clusters studied in this work. This radius can be estimated by the formula $R_{200} = \sqrt{3}\sigma/(10H(z)) \text{ Mpc}$ [15]. Then, if a cluster can be considered to be virialized within this radius, its mass M_{200} can be computed by the formula $M_{200} = 3G^{-1}R_{200}\sigma^2$, where σ is the dispersion of the line-of-sight velocities of the galaxies located within the R_{200} radius, and G is the gravitational constant. Thus, the measured mass of the cluster is $M_{200} \propto \sigma^3$. In our work, we first estimated the average line-of-sight velocity cz of the cluster and its dispersion σ , and then use the inferred dispersion to determine the R_{200} radius. We then determine the number of galaxies within this radius and redetermine cz , σ , R_{200} , etc. We move from the cluster and determine iteratively the dispersion of line-of-sight velocities of the galaxies and other parameters of the clusters within this radius. We consider galaxies with velocities deviating by more than 2.7σ from the mean velocity of the group (see, e.g., [4]) as field objects.

To find the radius R_{sp} , it is important to highlight the outskirts of galaxy systems. For this purpose, we present Figure 1 which describes in detail the structure and kinematics of galaxy cluster A 1318 (as an example). The panels of Figure 1 show: a) deviations of line-of-sight velocities of cluster members and field galaxies from the average radial velocity of the system plotted as a function of the squared clustercentric radius; b) the integral distribution of the number of galaxies as a function of the squared clustercentric distance; c) location of galaxies in the sky plane in equatorial coordinates; d) the histogram of the line-of-sight velocities of all galaxies within the R_{200} radius. The solid line shows the Gaussian corresponding to the dispersion of line-of-sight velocities of galaxies. The vertical lines show the radii: R_{sp} (dashed-and-dotted), R_{200} (short dashed), R_c (long dashed).

We are especially interested in panel b), where the projected cluster profile is shown, the integral distribution of the number of galaxies as a function of the squared clustercentric distance. This distribution makes it possible to visually reveal the dense core of the cluster, its more tenuous shell, and the external region where the distribution becomes linear (shown by the straight magenta lines in the figure) in the adopted coordinates, i.e., where the distribution of surrounding galaxies becomes uniform on the average [10]. The figure shows the radius of the virialized region, R_{200} , and the radius, R_{sp} , beyond which the steep growth of the cluster members ends and linear growth begins. We also marked with a long dashed line the central part (core) of the cluster of radius R_c , where the main steep increase in the number of galaxies is observed. The lower curve in the same figure shows the distribution of early-type galaxies brighter than $M_K = -21^m5$, which we use to refine the radius in question. Such galaxies are located, as a rule, in the central virialized regions of galaxy systems. R_{sp} , the splashback radius of the galaxy systems [7, 8] found by us, is the radius of the apocenters of the orbits of galaxies, originating in the central region of galaxy clusters. Thus, the radius R_{sp} separates galaxies which fall onto the cluster for the first time from collapsing galaxies that are already participating in establishing virial equilibrium. For our sample we measured

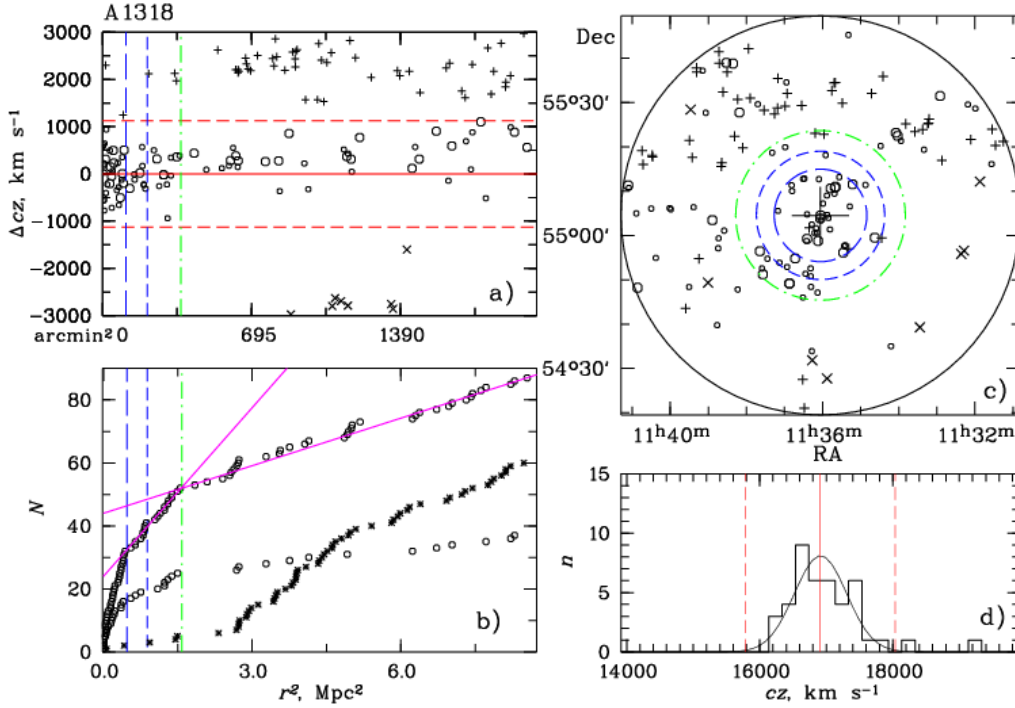


Figure 1: Distribution of galaxies in the cluster A 1318. The panel a) shows the deviation of radial velocities of galaxies from the average cluster radial velocity determined from galaxies within the radius R_{200} . The horizontal dashed red lines correspond to $\pm 2.7\sigma$ deviations, and the vertical blue short-dashed line marks the R_{200} radius; the blue long-dashed line marks the R_c radius, and the green dot-dashed line – the R_{sp} radius. The larger circles, plus signs, and crosses mark the galaxies brighter than $M_K = -24^m$, background galaxies, and foreground galaxies, respectively. The panel b) presents the integral distribution of the total number of galaxies (the upper curve) as a function of the squared projected distance from the cluster center. The lower curve shows the distribution of early-type galaxies brighter than $M_K < -21^m5$. The circles correspond to the galaxies denoted by the circles in the top panel a), the crosses show the distribution of field galaxies. The solid magenta lines show linear sections of the profile. The panel c) shows the sky distribution (in quatorial coordinates) of galaxies presented in the top panel a) (same designations are used). The colored circles highlight the regions with radii R_c , R_{200} , and R_{sp} . The studied region is bounded by a circle of radius $3.5R_{200}$ (solid black line). The large cross indicates the center of the cluster. The panel d) presents the distribution of radial velocities of all galaxies within R_{200} (the solid line shows the Gaussian for cluster members). The solid vertical line indicates the average radial velocity of the cluster, and the dashed lines correspond to $\pm 2.7\sigma$ deviations.

$\langle R_{sp} \rangle = 1.67 \pm 0.05$ Mpc with a variation range of $0.75 \div 4.24$, $\langle R_c \rangle = 0.78 \pm 0.03$ ($0.30 \div 2.00$) and $\langle R_{sp}/R_{200c} \rangle = 1.40 \pm 0.02$, or $\langle R_{sp}/R_{200m} \rangle = 0.88 \pm 0.02$ (given that $4R_{200c} \approx 2.5R_{200m}$). This value is consistent with results of simulations (see, e.g., [9]).

3. Results

We studied the dependences of the found radii R_{sp} and R_c on the properties of galaxy clusters. Figure 2 shows the dependence of $\log R_{sp}$ on the X-ray luminosity, $\log L_X$, and for comparison a

similar dependence for the radius $\log R_{200}$ is shown. The relations shown (straight lines) represent the average between forward and inverse regressions, when the independent variables are interchanged. The dashed lines show 1σ deviations from them. Note that rms deviation depends on the $\log R_{sp}$ radius less than on $\log R_{200}$. Red circles show merging clusters of galaxies with bimodal radial velocity distribution within the radius R_{200} . We can see that these systems do not differ from normal clusters of galaxies by location on the $\log R_{sp}$ – $\log L_X$ relation. The Table 1 shows the parameters of the relations we obtained: slopes, normalizations, and scatters.

We have noted in Section 1 the results of other authors (e.g., [9]), from which it follows that R_{sp} depends on the rate of accretion of dark matter particles on the clusters: at a rapid rate of mass accretion, this radius is close to the virial radius, that is, in our case to R_{200} .

Figure 3 shows the dependence of the radii ratios R_{sp}/R_{200} and R_{200}/R_c on the X-ray luminosity of systems of galaxies. Variations of the R_{sp}/R_{200} ratio have distinct boundaries for most systems of galaxies: $R_{sp}/R_{200} = 1.2 \div 1.6$ and $\log L_X = 42.5 \div 44.5$. We refer to galaxy systems with a radius ratio less than 1.15 (or $R_{sp}/R_{200m} < 0.71$) as objects with a rapid rate of mass accretion (RA), and the systems with a radii ratio greater than 1.6 (or $R_{sp}/R_{200m} > 0.99$) - as objects with a slow accretion rate (SA). There are 21 RA and 34 SA systems in our sample. RA systems are usually groups/clusters of galaxies with a non-Gaussian radial velocity distribution, with signs of merging with other groups and galaxies near the virial radius, for example: A 1270, A 1904, A 1991, NGC 2563. Among SA groups/clusters of galaxies there are rich galaxy systems such as A 1656, A 1795, A 2142, A 2029, poor galaxy systems such as NGC 7237, IC 2476, MCG-01-29, which collect matter (groups, galaxies, gas) from great distances from the center.

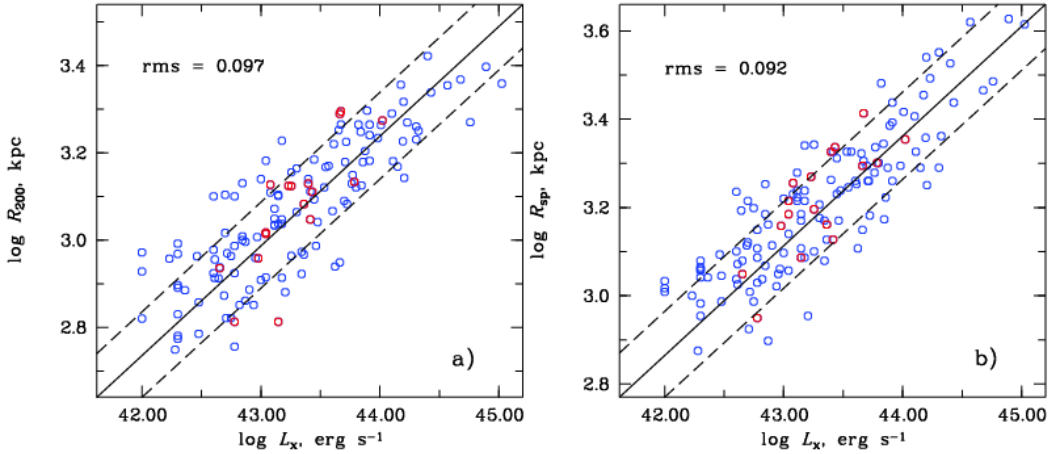


Figure 2: The radii R_{sp} (a) and R_{sp} (b) as functions of the X-ray luminosity. The solid lines correspond to the relations $R_{200} \propto L_X^{0.25}$ and $R_{sp} \propto L_X^{0.24}$. Dashed lines correspond to 1σ deviations from them. Red circles show groups/clusters of galaxies with bimodal distribution of radial velocities.

We have obtained the following results:

1. The boundary of the dark halo of groups/clusters of galaxies, the radius R_{sp} determined by galaxies, is proportional to the radius of the virialized region R_{200} and to the radius of the core region R_c with a slope close to 1.

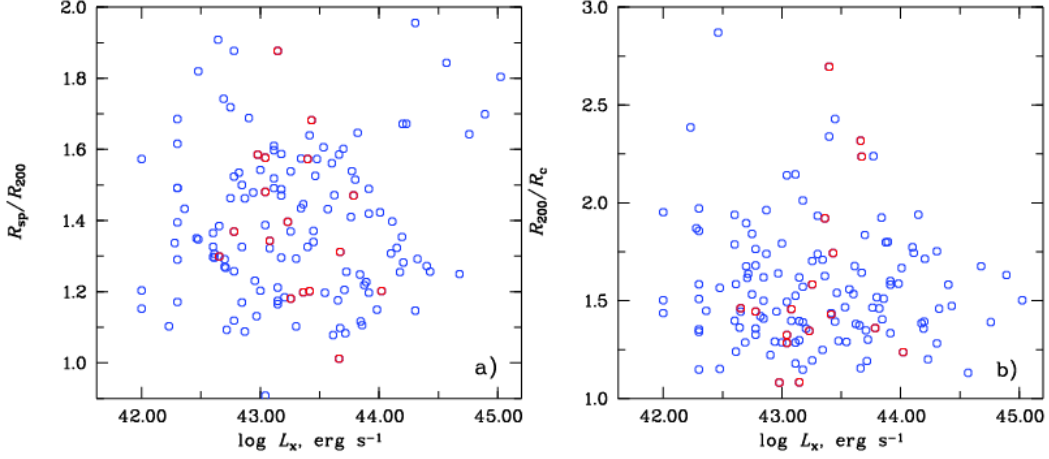


Figure 3: The ratios R_{sp}/R_{200} (a) and R_{200}/R_c (b) as functions of X-ray luminosity. Red circles show groups/clusters of galaxies with bimodal distribution of radial velocities.

2. All the radii we measured correlate with the X-ray luminosity of groups/clusters of galaxies and have similar slopes. Dependencies of the splashback radius on mass M_{200} and luminosity $L_{K,200}$ have a lower scatter.

Table 1: Best fit parameters

Relation	Slope	Normalization	Scatter
$\log R_{sp} - \log L_X$	0.24 ± 0.03	-7.39 ± 0.33	0.092
$\log R_{200} - \log L_X$	0.25 ± 0.04	-7.60 ± 0.34	0.097
$\log R_c - \log L_X$	0.26 ± 0.04	-8.45 ± 0.37	0.110
$\log R_{sp} - \log M_{200}/M_\odot$	0.32 ± 0.02	-1.42 ± 0.13	0.066
$\log R_c - \log M_{200}/M_\odot$	0.35 ± 0.03	-2.08 ± 0.17	0.086
$\log R_{sp} - \log L_K/L_\odot$	0.42 ± 0.03	-2.00 ± 0.17	0.074
$\log R_c - \log L_K/L_\odot$	0.44 ± 0.03	-2.66 ± 0.19	0.088
$\log R_{sp} - \log R_{200}$	1.00 ± 0.04	$+0.17 \pm 0.11$	0.064
$\log R_{sp} - \log R_c$	0.95 ± 0.05	$+0.46 \pm 0.14$	0.088

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