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Clusters of galaxies and their outskirts: star formation rate and stellar mass

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We investigate the specific star formation rate of galaxies as a function of distance from the cluster centre ($R < 3R_{200}$) in a sample of 40 groups and clusters of galaxies of the local Universe ($0.02 < z < 0.045$ and 300 $\mathrm{km\,s^{-1}} < \sigma < 950\ \mathrm{km\,s^{-1}}$). Using the SDSS Data Release 10, we find that the fraction of galaxies with quenched star formation is maximal in the central regions of the galaxy clusters and equals, on the average, 0.81 ± 0.02; it decreases to 0.44 ± 0.02 outside of the projected 'splashback' radius $R_{\rm sp}$, which we found from the observed profile of galaxy cluster, but still remains higher than that in the field by 27%. We measure the stellar mass of galaxy clusters corresponding to $K_{\rm s}$-luminosity (2MASX): $M_*/M_\odot \propto (L_K/L_\odot)^{1.010\pm0.004}$ ($M_K < -21^m.5$, $R < R_{200}$). We also found the dependence of the galaxy cluster stellar mass on halo mass: $M_*/M_\odot \propto (M_{200}/M_\odot)^{0.77\pm0.01}$.

Keywords: Clusters – galaxies: star formation – galaxies: evolution

1 Introduction

It is known from observations that the high-density central virialized regions of galaxy groups and clusters are populated by massive red early-type galaxies without star formation (see, e.g. Dressler 1980; Balogh et al. 2004; Kauffmann et al. 2004). It has also been established that the properties of galaxies in a cluster are related not only to their location depending on the distance from the center, but also to the time they enter to the cluster (e.g. Mahajan et al. 2011; Muzzin et al. 2014). The dependence of the properties of galaxies on the distance from the center have been studied in many works: the main result of which is a decrease in the star formation rate in galaxies towards the cluster center (see, e.g. Balogh et al. 1999; Balogh et al. 2000; Wetzel et al. 2012; Haines et al. 2015). Moreover, it was found (Balogh et al. 2000) that a decrease in the fraction of star forming galaxies is observed up to $5R_{200}$. The radius R_{200} is the radius of the sphere inside which the density in the

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system is 200 times higher than the critical density of the Universe. To explain this effect, model simulations (N-body) were performed of the star formation rate gradient along the radial distance from a galaxy cluster centre. The simulations showed that a considerable fraction of galaxies beyond the cluster virial radius have once been in their central regions.

In order to establish the variation of the specific star formation rate along the normalized radius of systems (up to $3R/R_{200}$), we used in our study a sample of 40 galaxy groups and clusters with registered X-ray emission, including systems of galaxies from the Leo and Hercules supercluster regions, as well as several nearby systems: clusters A1367, A1656 and eight groups of galaxies considered earlier in Kopylova and Kopylov (2015).

Section 2 describes our measurements of the total stellar mass of the system of galaxies within the radius R_{200} and compares the obtained stellar mass with the dynamical mass. In Section 3 we describe the procedure of selecting the region in the outskirts of galaxy clusters (in units of radius $R_{\rm sp}$). In Section 4 we show variations of the fraction of quenched galaxies (QG) along the radius of the systems. In the Conclusion, we list the main results. In this work, we used the following cosmological parameters: $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, $H_0 = 70$ km s^{-1} Mpc^{-1}.

2 Stellar mass in galaxy clusters

In order to determine the total stellar mass of a system of galaxies within the radius R_{200} ($M_K < -21^m.5$), we used the results of stellar mass data for galaxies from the SDSS DR10 archive, which were obtained by using FSPS models of Conroy et al.

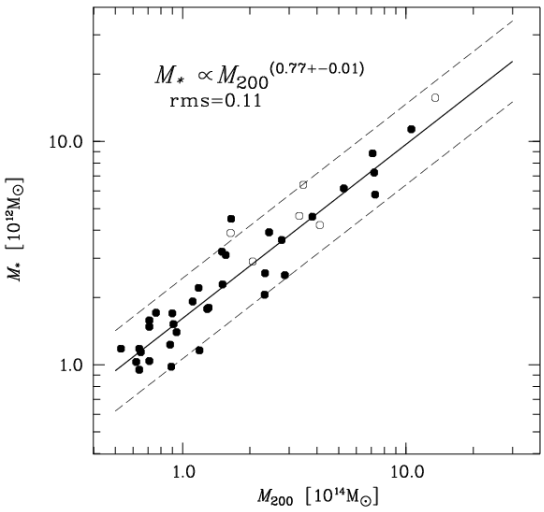


Figure 1 Correlation between the total stellar mass and the halo mass within R_{200} for galaxy clusters. The solid line corresponds to the regression ratio $M_*/M_\odot \propto (M_{200}/M_\odot)^{0.77\pm0.01}$, and the dashed lines show 2σ deviations from it. The empty circles show the galaxy clusters from Kopylova and Kopylov (2018).

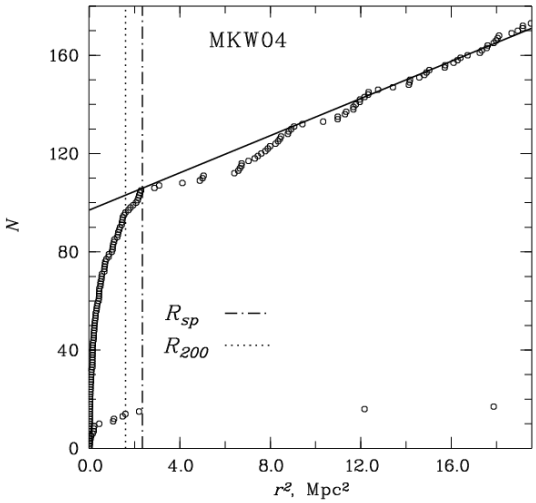


Figure 2 Integral distribution of the total number of galaxies as a function of squared clustercentric distance in the cluster MKW04. The radii R_{200} and $R_{\rm sp}$ are shown by the dotted and dot-dashed lines. The lower points correspond to early-type galaxies brighter than $MK < -21^m.5$.

(2009) fit to SDSS photometry (corrected for extinction) in u, g, r, i, z. We should note that not all galaxies which we included in the sample have spectral data in SDSS DR10 (which includes stellar masses). When no stellar mass measurements were available, we estimated them approximately from the $u - r$ and $g - r$ colors, absolute magnitudes, and the *fracDeV* parameter. In our earlier works (Kopylova and Kopylov 2013, 2015; Kopylov and Kopylova 2015) we used the 2MASX data (Jarrett et al. 1997) to determine the $K_{\rm s}$-luminosities of the considered galaxy clusters within R_{200}. We compared the derived $K_{\rm s}$-luminosities with the stellar masses presented in SDSS DR10 and obtained for our sample the following relation: $\log M_{*,200} = (1.010 \pm 0.004) \log L_{K,200} - (0.144 \pm 0.050)$ with a standard deviation of 0.05. The dependence of the stellar mass of the galaxy clusters on their dynamical mass, which we determined from the radial velocity dispersion, has a form of $\log M_{*,200} = (0.77 \pm 0.01)(\log M_{200} - 14.5) + (12.595 \pm 0.12)$ with the standard deviation of 0.11 and is shown in Figure 1. Masses and luminosities in all the expressions are given in $M_\odot$ and $L_\odot$.

3 Outskirts of galaxy clusters

We determined the dynamical characteristics of the studied systems of galaxies: radial velocity, radial velocity dispersion, cluster (halo) mass for a virialized region of radius R_{200}. In our study, it is important to isolate the nearest outskirts of the galaxy systems: in addition to the R_{200} we determine the 'splashback' radius (e. g. Chang et al. 2017) $R_{\rm sp} > R_{200}$.

Figure 2 shows the projected cluster profile. As the distance from the cluster center increases, we observe first a sharp increase in the number of galaxies, and then, beyond

the limits of the virialized region (R_{200}), its linear growth (shown in the figure by a straight line). The radius $R_{\rm sp}$ corresponds to the distance from the center where the sharp increase in the number of cluster members changes to linear. We assume that this radius corresponds to the apocenter of orbits of galaxies that entered into the virialized region of the cluster and then flew out to come back again. The radius $R_{\rm sp}$ obtained by us from the integral distribution of the number of galaxies as a function of squared distance from the cluster center is equal, on average to $(1.54 \pm 0.06)R_{200}$. (descibed in more detail in Kopylova and Kopylov (2018, 2019)).

4 Specific star formation rate in galaxy clusters

The specific star formation rate (sSFR) in the galaxy is determined by the integral star formation rate divided by its stellar mass: $sSFR = SFR/M_*$. The SDSS DR10 catalog gives the results of determining the specific star formation rate in the galaxies. A minimum is usually found in the $\log sSFR$ distribution which separates the galaxies actively forming stars (active galaxies) from galaxies in which star formation is suppressed (quenched galaxies, QG). A clear bimodality of the distribution and the minimum corresponding to $\log sSFR$ yr^{-1} = –11 are found in Wetzel et al. 2012 (based on SDSS DR7). In our case $\log sSFR$ yr$^{-1} \sim -10.75$ correspond to the minimum for the considered clusters (Kopylova and Kopylov 2019). Figure 3 shows the fraction of quenched galaxies QG as a function of projected clustercentric radius normalized to radius R_{200}. Figure (a) shows the total fraction of QG without separation in bins of galaxy stellar mass, figures (b–e) show the fraction of QG for each stellar

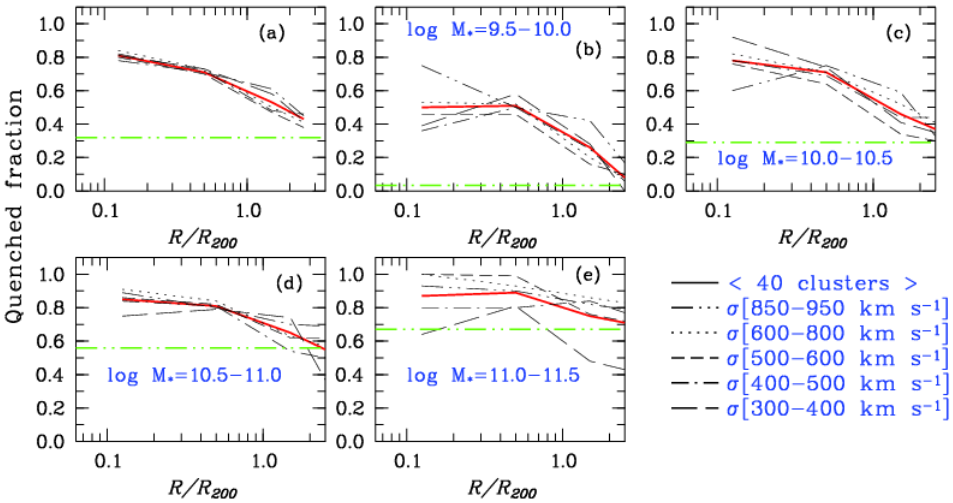


Figure 3 Fraction of galaxies with quenched star formation (QG) ($\log sSFR\ yr^{-1} < -10.75$) as a function of clustercentric distance. The clusters are groups according to σ. The solid red line corresponds to the average value for all galaxy systems. Panel (a) shows QG, found from all the galaxies, panels (b-e) - from galaxies binned by stellar mass. In each panel, the dot-dot-dashed green line shows the QG in the field.

mass bin. Different lines show the variations of the fractions of QG, corresponding to the radial velocity dispersion bins. The total fraction of QG varies from the average value 0.81 ± 0.02 in the central regions of clusters to 0.44 ± 0.02 beyond the radius $R_{\rm sp}$. We found that the fraction of QG in the field is equal 0.32 ± 0.07, which is lower than that in the outskirts of clusters of galaxies.

5 Conclusions

The observational data show that galaxies in groups and clusters differ from field galaxies. In this work, we investigated the central regions and nearest outskirts of galaxy systems (up to $3R_{200}$ in projection). For the considered galaxy cluster sample we determined: the stellar mass within R_{200}, the specific star formation rate, the quenched galaxy fraction along the clustercentric radius in comparison with field data. Our main results are the following. The total stellar mass of galaxies in clusters correlates with total dynamical mass M_{200}: $M_*/M_\odot \propto (M_{200}/M_\odot)^{0.77}$. This indicates that the efficiency of star formation in galaxies decreases with increasing mass of cluster. The fraction of galaxies with quenched specfic star formation rate is maximal in the central regions of clusters and on the outskirts beyond $R_{\rm sp}$ is higher than that in the field by about 27%. The main hypothesis explains the quenching of star formation of galaxies beyond the $R_{\rm sp}$ by the fact that galaxies in the groups that fall into the cluster have already undergone pre-processing, having lost their gas as a result of ram pressure (e.g. Wetzel et al. 2012; Haines et al. 2015).

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