Morphological Properties of Isolated Galaxies vs. Isolation Criteria

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We studied the morphological properties of isolated galaxies samples in dependence on the isolation parameter and properties of primary catalogs. With this aim we identified the samples of single and isolated galaxies from SDSS DR5 (Single and QIsol) with the 3D Voronoi tessellation method (Elyiv et al. 2009). We found that in comparison with other samples of isolated galaxies, the QIsol sample contains an excess of late-type galaxies, especially with a low luminosity and BCG/Im/Irr morphology. We also showed that the fractions of early type galaxies in QIsol SDSS DR5 sample and samples 2MIG (Karachentseva et al. 2010) and CIG (Karachentseva et al. 1973, Hernandez-Toledo H. M. et al. 2008) are in a good agreement (16-19%), but Allam's (Allam et al. 2005) and Prada's (Prada et al. 2003) SDSS DR1 samples show a higher excess of the early type galaxies that can be explained by the selection criteria and morphology definition method. We found a weak relation between isolation parameter and color index for the Single sample that may indicate that even in the low dense environment the morphology density relation is observed. We conclude that morphological properties of the resulting sample of isolated galaxies are highly dependent on the primary catalogue from which the galaxies were selected. Moreover, the selection criterion is also important but plays a secondary role in the resulting morphological content, color indices distribution and other parameters of the isolated galaxy samples. Only four galaxies are common in the 2MIG, QIsol, and CIG samples, namely UGC5184, UGC6121, UGC8495, and UGC9598, that allows to consider them as really most isolated galaxies.

1 Introduction

What is the relation between intrinsic and environmental influences on galaxy properties? What is the mass-to-luminosity ratio and star formation rate for the isolated galaxies as compared with galaxies in groups and clusters? Did the morphological type of isolated galaxies not change during their evolution? What may we conclude in favor of various cosmological scenario and their modifications by studying and observing the dark halo of isolated galaxies in a wide region of the electromagnetic waves? What is the median lifetime for single galaxies to be really isolated galaxies? How should the existing isolation criteria parameters be unified to create a perfect sample of isolated galaxies in the Universe? Answers to these and many others questions are highly important because isolated galaxies are the unique effective observational and theoretical laboratories for testing the galaxy formation and evolution. Meanwhile we should develop a mask of parameters of this "laboratory" which still are not defined strongly because of dependence on the different isolation criteria and primary catalogues.

Under *isolated galaxies* we understand usually galaxies located in very low density environments and selected by the defined criteria. On the one hand, the term *isolated galaxy* is relative: for example, velocity criterion ΔV=700 km/s allowed to consider both galaxies with ΔV= 2 km/s and ΔV=698 km/s as neighborhood equivalent. On the other hand, when we use parameters, which characterize the galaxy isolation degree, our approach depends mainly on the chosen observed survey/catalog, its homogeneity and completeness. In this way we are able to describe parameters of isolated galaxies sample more correctly.

Various approaches were proposed to identify isolated galaxies using available galaxy data bases, surveys and catalogues. Karachentseva (1973) inspected visually the environment of each galaxy from the CGCG catalogue using the POSS and created the uniform sample of 1050 isolated galaxies (CIG) in the Northern sky. She used the selection condition in which a galaxy with angular diameter a_1 is considered to be isolated if all significant neighbors with angular diameters a_i in the range ($4a_1 > a_i > a_1/4$) lie a distance r_{1i} from it of at least $20a_i$. Properties of CIG galaxies are widely discussed and used for comparison with galaxies in rich systems (see, for example, Pamela et al. 2004; Karachentseva et al. 2005; Verley et al. 2007; Hernandez-Toledo et al. 2008). For example, Verley et al. (2007) quantified the isolation degree of CIG galaxies. Such approach allowed the authors to find the most isolated galaxies in CIG sample, which evolution is mainly driven by intrinsic properties and not by the external influence of their environment. Empiric criteria by Karachentseva (1973) with small mod-

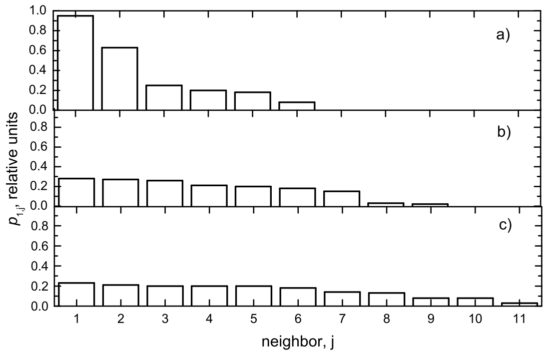

Fig. 1 Distribution of parameter $p_{1,j}$ for the galaxy in different environment according to 3D Voronoi tessellation

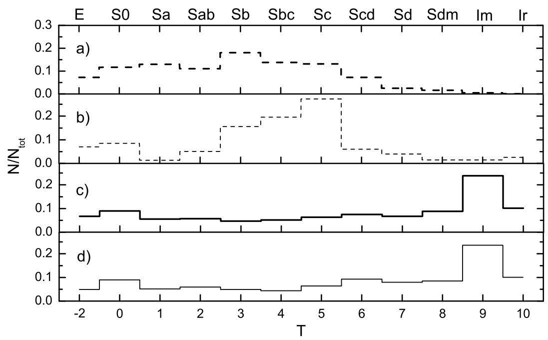

Fig. 2 Comparison of morphological content of galaxy samples: a) 2MIG, b) CIG (estimation by Hernandez-Toledo et al. 2008), c) QIsol, N=600, d) MIsol, N=389

ifications were also used by Allam et al. (2005) for identifying isolated galaxies in the SDSS DR1 and by Karachentseva et al. (2010) for selection of isolated galaxies on the basis of the Two Micron All-Sky Survey (2MASS). Deng et al. (2009) applied these criteria to the sample of SDSS DR6 galaxies for defining the influence of selection criteria on the properties of isolated galaxies. Prada et al. (2003) found isolated galaxies and their smaller satellites in SDSS using few variations of limitation by differences on velocity ΔV, projected distance Δr, and magnitudes Δm. Similar approach was applied by Reda et al. (2004). The authors extracted elliptical isolated galaxies using Lyon Extragalactic Data Base (LEDA) and boundary conditions ΔV=700 km/s, Δr=0.67 Mpc between possibly *isolated* galaxy and its *significant* neighbors. As an additional condition in their criteria for isolated galaxy was the absence of neighbors in 2.0 B-band magnitudes interval.

Besides the tasks of isolated galaxies identification and studying their role in the large-scale structure formation and evolution, the principal point is also their mass-to-luminosity ratio. It raises questions about how many isolated galaxies acquire and keep dark matter halo as well as how long such a halo is extended. In our previous work by Elyiv et al. (2009) we applied the modified 3D Voronoi tessellation method to the SDSS DR5 galaxy survey for identifying *single* galaxies, *pairs* and *triplets* in such a way that each of these systems was characterized by their own *isolation* parameter. One of our conclusion as concerns with mass-to-luminosity ratio for the loose galaxy groups was that isolated galaxies are two times less luminous than galaxies in isolated pairs and triplets (see also Melnik et al. 2009). Moreover, the luminosity-density relation is observed even in such small groups as pairs and triplets (the richer system, the greater mass-to-luminosity ratio). Because of the strong correlation between galaxy morphology, luminosity and local environment, we decided to undertake a series of works on isolated galaxies. The primary goal of this paper is to study morphological properties of current samples of Single galaxies in context of their isolation parameter. The secondary goal is to compare how the properties of isolated galaxies samples depend on selection criteria and properties of catalogues from which these samples were compiled. Among such samples of isolated galaxies we took into consideration the following: Sample of isolated galaxies on the basis of SDSS DR5 (Elyiv et al. 2009), Catalogue of Isolated Galaxies on the basis of CGCG (Karachentseva 1973), 2-Micron Isolated Galaxies (2MIG) catalogue on the basis of 2MASS XSC (Karachentseva et al. 2010), and two Samples of isolated galaxies on the basis of SDSS DR1 (Prada et al. 2003) and (Allam et al. 2005).

2 Sample of Single SDSS DR5 galaxies and isolation parameter via 3D Voronoi tessellation

The sample of Single galaxies was extracted from the primary volume-limited SDSS DR5 galaxy sample ($2500 < V_h < 10000$ km/s). It is known that completeness of SDSS is poor for the bright galaxies because of spectroscopic selection criteria and the difficulty of obtaining correct photometry for object with large angular size. Exactly by this reason we have tried to decrease of this effect's influence due to limiting of our sample $V_h > 2500$ km s^{-1}, i.e. in the way not to take into account nearest objects with the large angular diameter. Such a volume limiting also helps us to avoid influence of Virgo cluster where strong peculiar motion exists. We checked additionally all pairs of galaxies with a small angular resolution and excluded identical objects (parts of galaxies), which are presented twice and more in SDSS survey. All galaxy velocities V_h were corrected for the Local Group centroid V_{LG}. When we had applied the high-order Voronoi tessellation method to SDSS catalogue we limited our sample 3000 km s^{-1} $\leq V_{LG} \leq$ 9500 km s^{-1}. We did not consider also galaxies that located within 2^{o} near borders, because the correct estimation of Voronoi cell volume is not possible in this case. As result, our volume-limited sample is complete up to 17.7^{m} but contains also about 100 more fainter galaxies. The final number of galaxies in the sample is 6786.

After applying the second order 3D Voronoi tessellation method for identifying loose galaxy groups we divided our sample on two subsamples: galaxy Pairs (65%) and Singles (35%); galaxy Triplets were selected separately (details on this method see in Elyiv et al. 2009). Below we give a brief explanation as concerns with choosing the isolation parameter for Single galaxies via modified 3D Voronoi tessellation.

Each pair of galaxies i, j is characterized by the dimensionless parameter $p_{i,j}$:

$$p_{i,j} = \frac{\sqrt[3]{V_{i,j}}}{m_{i,j}}, \quad (1)$$

where $V_{i,j}$ is the volume of second order Voronoi cell, $m_{i,j}$ is the spatial distance between galaxies i and j.

Fig. 1 shows the variation of parameter $p_{i,j}$ with increasing the galaxy isolation degree. The distribution of dimensionless parameters $p_{1,j}$ for arbitrary chosen galaxy "1" and its neighbors "j" for randomly distributed galaxies is presented in Fig. 1a. Fig. 1b and 1c show the distributions of values $p_{1,j}$ for the same galaxy "1", but artificially moved away its neighbors "j" in such a way that the galaxy "1" in Fig. 1c is more isolated than in Fig. 1b. We see, the larger the degree of galaxy isolation, the greater is the number of neighbors, but these neighbors are located far away. We chose isolation parameter s as the mean value of all parameters p_j of this galaxy (here we put away index "1"):

$$s = \frac{\sum_{j=1}^{k} p_j}{k}, \quad (2)$$

where k is the number of neighbors. Therefore the smaller is s value, the more isolated is the single galaxy,

Our sample of Single galaxies compiled by 3D Voronoi tessellation method consists of 2394 galaxies, which are characterized by their own isolation parameter s. We will refer below to the Quarter of galaxies with the smallest values of isolation parameter as to the QIsol sample (600 galaxies).

3 Comparison of morphological properties and color-indices of isolated galaxies from different samples

Sample of isolated SDSS DR5 galaxies. We checked the morphological content of the QIsol sample by the visual inspection of images and spectra of galaxies using SDSS Navigate and Explore tools, respectively. Information from the NED and LEDA data bases and the Digital Sky Survey was also taken into consideration to define the galaxy morphological types. For morphological classification we have used de Vaucouleurs' numerical scale. All ellipticals were signed as -2, the Blue Compact Galaxies (BCGs) were attributed to type 9 (see Fig. 2 for the rest scale). We also made an additional check of the neighborhood around QIsol galaxies to identify possible physical companions. As companions we have considered all objects within $\triangle$V=600 km/s and/or $\triangle$r=0.6 Mpc distance from QIsol galaxies as well as significant neighbors without velocities by Karachentseva's criterion (1973) (see Introduction). From 600 QIsol galaxies, 389 don't have any companions. We will refer this subsample of QIsol galaxies as the Most Isolated galaxies (MIsol).

Comparison of galaxy morphological content in various samples of isolated galaxies. The morphological type distribution of QIsol and MIsol samples in comparison with CIG and 2MIG samples are presented in Fig. 2.

All four samples have a comparable content of early-type galaxies: 19% in 2MIG, 16% in CIG and QIsol, 14% in MIsol. On the other hand, the morphological content of late-type galaxies is completely different. The maxima of morphological type number distributions for MIsol and QIsol samples are in the Im type (9), which mostly contains Blue Compact Galaxies (BCGs) with strong emission lines. Late-type CIG galaxies are mostly Sb-Sc spirals, but the 2MIG sample contains nearly the same fraction of spiral galaxies of Sa-Sc types with a maximum in the Sb type. As the morphological content of MIsol and QIsol samples is practically the same (Fig. 2c and 2d), we will consider below only the QIsol sample .

We suppose that these peculiarities in morphological type distributions are exactly due to the principal differences in the primary catalogues of galaxies from which the isolated galaxies samples were selected. Namely, the 2MIG catalogue was created on the base of near-infrared 2MASS survey. That is why 2MIG galaxies tend to be of early morphological type. Our sample of single galaxies (and its most isolated QIsol subsample) is formed based on the SDSS DR5 catalogue, which contains much more faint galaxies ($\sim$17.7 mag and even fainter) than CIG galaxies ($<$15.7 mag). This circumstance may explain a larger presence of more massive Sb-Sc spirals in the CIG sample in comparison with a huge number of BCGs in the QIsol sample.

We may conclude that the morphological type test is sensitive enough to the selection criteria for isolated galaxies and reflects the properties of the primary catalogues.

Comparison of galaxy color-indices in various samples of isolated galaxies. It is known that galaxy morphological types are highly correlated with color-indices and luminosities because of the difference in stellar population and galaxy mass: early type galaxies tend to be redder and more massive than late type galaxies. The color distributions and color-magnitude diagrams are the most effective tools for morphological galaxy classification on blue and red populations especially for SDSS, where magnitudes in five color bands are available (Park & Choi 2005, Fukugita et al. 2007, Lintott et al. 2008 and others). We decided to use a similar approach for defining morphological content of our samples of comparison. The concentration index $CI = R90/C50$ is widely used also for this aim, but we found that this parameter is less effective in our case (see below).

Color-indices - morphological type dependence for QIsol sample is presented in Fig. 3. We indicate the strong correlation between these two galaxy parameters: the mean

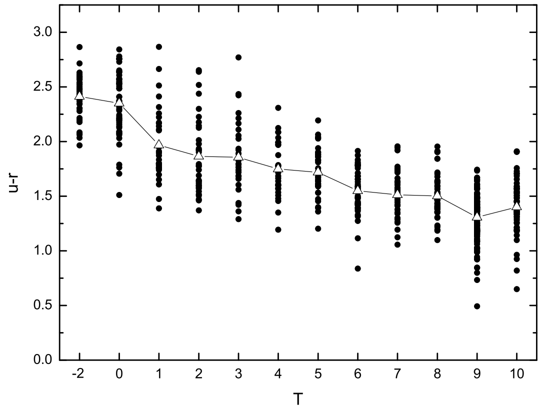

Fig. 3 Color indices $u-r$ - morphological type relation for QIsol sample. Mean values of color indices are marked by open triangles

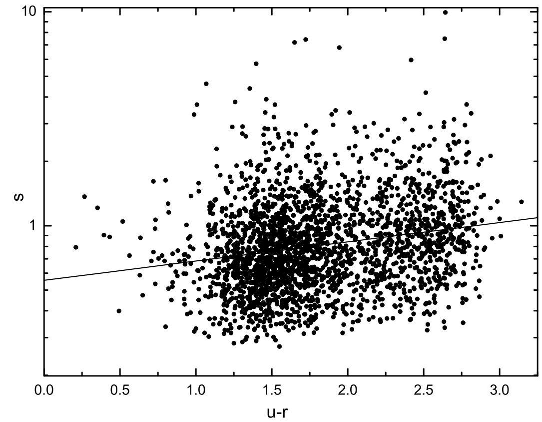

Fig. 4 Parameter isolation - color indices $u-r$ relation for N=2394 Single galaxies: logs = 0.09(u-r)-0.26, R=0.22, SD=0.21.

values of color indices are found to be decreasing with increasing morphological type number. Exception is the type 9, which characterizes BCGs. A stellar population of type 10, which includes the Low Surface Brightness (LSB) galaxies, is more close to type 8, which characterizes Sdm/Sm galaxies. Logically, the types 9 and 10 should be changed by places. The mean values and standard deviations of color indices for different morphological types are 2.41±0.20 (E), 2.35±0.30 (S0), 1.97±0.33 (Sa), 1.87±0.35 (Sab), 1.86±0.36 (Sb), 1.75±0.25 (Sbc), 1.72±0.22 (Sc), 1.55±0.21 (Scd), 1.51±0.21 (Sd), 1.50±0.19 (Sdm), 1.31±0.21 (Im/BCG), 1.40±0.23 (Irr).

The dependence of isolation parameter s on color indices for Single sample is given in Fig. 4. A weak dependence is observed: the greater the isolation parameter (denser environment), the greater the value of $u-r$ color indices (galaxies tend to be early-type ones). The existence of this weak relation (correlation coefficient is 0.22) may indicate that even in the low dense environment the morphology-density relation is observed. On the other hand it means that only highly isolated galaxies from QIsol sample are not influenced by environment.

We used color indices for estimating the morphological content of various SDSS samples of isolated galaxies for comparison. Comparison of $u-r$ color indices distributions for QIsol, sample N2 by Prada et al. (2003), sample by Allam et al. (2005) is presented in Fig. 5. One can see that the distributions are completely different. Galaxies from the QIsol sample are shifted to the blue side, galaxies from Prada's sample show excess of redder galaxies, and galaxies from Allam's sample are in the middle part of distribution. Two peaks with border u-r≈2.25 are clearly observable in all three SDSS samples of isolated galaxies. The M_B-color index relation for our QIsol sample, where we marked galaxies with visually inspected morphology, is shown in Fig.6. This parameter was estimated from the relation between B, g, and r magnitudes as given by Yasuda et al. (2001).

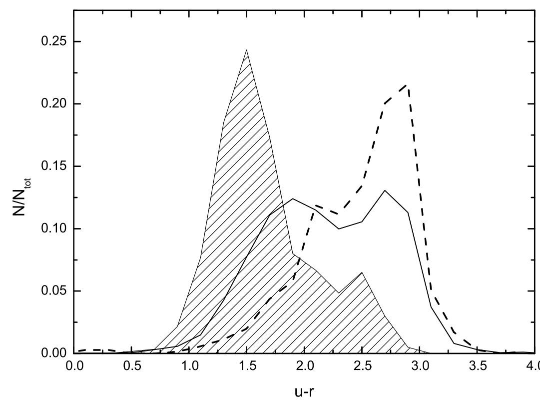

Fig. 5 Distribution of color indices for SDSS samples of isolated galaxies: QIsol (shaded area), Allam et al. (2005) (solid line), and Prada et al. (2003) isolated galaxies (dash line)

Analysis of absolute magnitude - color index distribution for the sample of QIsol galaxies in Fig. 6 allows to conclude that early type galaxies (-2 and 0) are more luminous and redder, while late type galaxies (from 7 to 10) have significantly weaker luminosities and bluer colors; spirals (from 1 to 6) have intermediate values of absolute magnitude and color indices.

4 Discussion

The data on the color indices dispersion, which characterize the given morphological type number, allows us to estimate the content of early types ($u-r > 2.2$), spirals ($1.5 < u-r < 2.2$) and late types ($u-r < 1.5$) galaxies in Prada's and Allam's samples. Content of visually defined morphological types in the given u-r diapasons corresponds

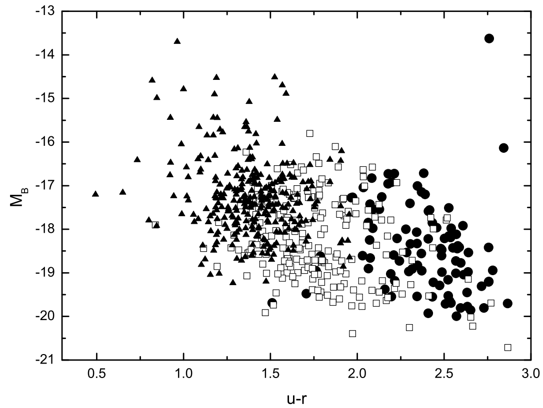

Fig. 6 Absolute magnitude - color index distribution for the sample of QIsol galaxies: -2 and 0 morphological types marked as circles, from 1 to 6 are open squares and from 7 to 10 are triangles)

to 74%, 72% and 72%, respectively. As it was aforementioned, we would like to add some important commentary on the usage of the concentration index to estimate a morphological content in these samples. Allam et al. (2005) and Deng et al. (2009) used the concentration indices $CI > 2.5$ and $CI > 2.86$, respectively, to define the early types galaxies in their samples. In case of applying the $CI > 2.5$ criterion to our QIsol galaxy sample we should obtain about 37% of ”early type” galaxies, but a fraction of visually defined early types galaxies in this sample is 39% only (percent from a total number of visually classified galaxies of -2 and 0 morphological types). In other words, such ”early type” subsample of QIsol galaxies should be contained of 16% of galaxies with -2 and 0 visually classified types, 51% of Sa-Sdm spiral galaxies, 22% galaxies with type 9 and the rest of Irr galaxies. In case of the usage of the more strong criterion $CI > 2.86$, the subsample of ”early type” QIsol galaxies should be contained of 18% from the total number, besides the fraction of visually defined early type QIsol galaxies is 22%. Analyzing these pre-estimations, we justified in favor of the usage of *”u-r indices”* as a method for the morphological classification of QIsol SDSS DR5 sample.

Table 1 contains the data on the percent of galaxies within the chosen morphological type diapason and $u - r$ quantities for QIsol galaxy sample, as well as about the morphological content for Prada’s and Allam’s isolated SDSS galaxy samples. For correctness of comparison we used only such data that correspond to redshifts of QIsol sample. The mean M_B values are noted in the last rows.

One can see from Table 1 that the estimated morphological content of all the three isolated SDSS galaxy samples is completely different.

Galaxies from Prada’s sample have mostly ”early type” morphology and more luminous on average that can be predetermined by the selection condition ($M_B > -19.5$ mag.

Table 1 Morphological content of the SDSS isolated galaxy samples (DR5 sample - QIsol - (Elyiv et al. 2009), DR1 samples - Allam (Allam et al. 2005) and Prada (Prada et al. 2003))

Characteristic	QIsol	Allam	Prada
Visually estimated morphology			
Early-type: -2 ÷ 0	16%	-	-
Spirals: 1 ÷ 6	35%	-	-
Late-type: 7 ÷10	49%	-	-
Estimated from color indices			
Early-type: $u - r > 2.2$	15%	50%	73%
Spirals: $1.5 < u - r < 2.2$	43%	41%	23%
Late-type: $u - r < 1.5$	42%	10 %	3%
$< M_B >$			
Early-type:	-18.42	- 18.21	-20.39
Spirals:	-18.24	-18.01	-20.39
Late-type:	-17.28	-17.63	-20.39

In the work by Balogh et al. (2004) a clear dependence of the shape of $u - r$ bimodal distribution on the galaxy luminosity and local density was demonstrated. It helps to explain that the redder (early type) galaxies with such high magnitudes dominate in distribution. On the other hand, the fraction of galaxies in the red diapason of distribution at the fixed luminosity depends strongly on the local density. Perhaps, in this case we deal rather with the question of selection riterion terminology, because of among the bright isolated galaxies with not significant satellites, Prada et al. (2009) considered systems likely galaxy groups with one dominated galaxy. The Allam’s sample is comparable with QIsol galaxies by magnitudes but also has excess of ”early type” galaxies. Partially the use of non-universal boundary $u-r$ conditions may explain this result. In fact, according to Fig. 2, 14 spiral galaxies of Sa-Sb types fall in the region of ”early types” with $u-r > 2.2$. Taking into account the ratio between the fraction of visually classified early type galaxies and the contamination of spiral galaxies we suppose that the fraction of really early type galaxies in Allam’s sample is about of 37%.

Concerning the direct cross-correlation of these three isolated SDSS galaxy samples, we have found that 23 galaxies are common in the 2MIG and QIsol samples (it composes 30% from the total number of 2MIG galaxies, which fall in our SDSS region); 10 of CIG galaxies coincide with QIsol (27%); 9 QIsol galaxies are common with Allam’s isolated galaxies sample (14%). It is interesting that any common galaxies between 2MIG and Allam samples was found. All 34 isolated galaxies with fainter satellites from Prada’s sample that fall in our region coincide with our SDSS Pairs and Triplets selected by 3D Voronoi tessellation method. Only four galaxies are common in three samples (2MIG, QIsol, and CIG), namely UGC5184, UGC6121, UGC8495, and UGC9598, that allows to consider them as really most isolated galaxies. Deng et al. (2009) noted that because morphology most strongly depends on the local environment, rather than on other characteristics, the test on morphology is the better choice for studying the environmental dependence of galaxy properties.

5 Conclusion

We have considered the morphological content of galaxies with the highest level of isolation (QIsol) from our sample of Single galaxies, which was selected from SDSS DR5 with the 3D Voronoi tessellation method (Elyiv et al., 2009). We found that in comparison with other samples of isolated galaxies, the QIsol sample contains an excess of late-type galaxies, especially with a low luminosity and BCG/Im/Irr morphology. This result is in agreement with conclusions by Balogh et al. (2004) and Patiri et al. (2006), who obtained the excess of blue type low luminous galaxies in voids. It is interesting that such a result is confirmed for both volume-limited and magnitude-limited samples. BCGs are objects with ongoing star formation and low metalicity, which are the ideal laboratories for studying the evolution of massive stars (Isotov & Thuan 2009). Zitrin et al. (2009) showed that isolated BCGs have a significantly larger star formation rate than dwarf galaxies in the Virgo cluster that is also the evidence of their intrinsic evolution, but not the environmental influence. Our result is an additional confirmation that the properties of isolated BCGs can be interesting both in the context of their star formation rate and chemical composition.

We also showed that the fractions of early type galaxies in QIsol SDSS DR5 sample and samples 2MIG (Karachentseva et al. 2010) and CIG (Karachentseva et al. 1973, Hernandez-Toledo H. M. et al. 2008) are in a good agreement (16-19%), but Allam's SDSS sample (Allam et al. 2005) and Prada's SDSS sample (Prada et al. 2003) shows a higher excess of the early type galaxies. In case of Prada's sample it can be explained by the selection limit condition on luminosity. On the other hand, we see that the use of $u-r$ color indices distribution for the morphological classification of QIsol sample led to the underestimation of contamination of Sa-Sb galaxies with massive buldges in $u-r>2.2$ diapason. Deng et al. (2009) concluded that Karachentseva's (1973) criterion admits 35% of galaxies to belong to groups. So, the excess of early type population in Allam's SDSS DR1 sample could be attributed to this selection effect.

We estimated the morphological content of the sample of Single galaxies (where a weak morphology density relation is observed) by chosen criterion and found 25% "early types" galaxies in our sample that is higher than for QIsol SDSS sample. This is an additional evidence of a strong dependence of the morphology on environment even in the relatively low density regions. Recently Karachentseva et al. (2010) finished their work to create the catalogue of isolated galaxies (2MIG) on the basis of 2MASS XSC. 2MIG sample contains only 19% of early type galaxies. Except of Karachentseva's (1973) criterion, the authors used the visual inspection of isolated galaxies. We can conclude that even in our time of high technologies, visual inspection is very helpful for searching significant neighbors of isolated galaxies (see also works of AMIGA group by Verley et al. 2007; Hernandez-Toledo et al. 2008)

Our analysis allows to conclude that morphological properties of a resulting sample of isolated galaxies are highly dependent on the primary catalogue, from which these galaxies were selected. Moreover, the selection criterion (isolation parameter) is also important but plays the secondary role in the estimation of morphological content, color indices distribution and other parameters of the isolated galaxy samples. So, the creation of the perfect sample of isolated galaxies is of a high importance.

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