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THE GALAXY POPULATION IN VOIDS: ARE ALL VOIDS THE SAME?

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ABSTRACT

The influence of under-dense environments on the formation and evolution of galaxies is studied by analysing the photometric properties of ~ 200 galaxies residing in voids, taken from our SDSS DR10 void catalog up to z ~ 0.055. We split void galaxies into two subsamples based on the luminosity density contrast of their host voids: 'sparse void' $\delta_s = \delta < -0.95$ and 'populous void' $\delta_p = \delta > -0.87$. We find that galaxies in sparse voids are less massive than galaxies in populous voids. The luminosity distribution of galaxies in populous voids follows the same distribution observed across the SDSS survey in the same redshift range. Galaxies in the sparse voids are also bluer suggesting that they may be going through a relatively slow and continuous star formation. Additionally, we find that the luminosity function of galaxies in populous voids is represented with the Schechter function whereas the same does not hold for sparse voids. Our analysis suggests that the properties of a host void plays a significant role in the formation and evolution of the void galaxies and determining the large scale evolution of voids is an important step to understand what processes regulate the evolution of galaxies.

Subject headings: cosmology: observation – void: environment – galaxies: formation – galaxies: luminosity function

1. INTRODUCTION

One of the main outstanding problems in observational cosmology is to understand how galaxy properties are influenced by their environments and evolve with cosmic time. For instance, in over-dense regions 'groups/clusters', distinct mechanisms such as tidal force, ram pressure stripping and harassment play a fundamental role in galaxy star formation rate, color and morphology (e.g. Veilleux et al. 2005; Kormendy et al. 2009). By incorporating these quenching mechanisms, galaxies in higher density regions tend to be redder and earlier type, have lower star formation rate and are more strongly clustered. Some of these trends might lead to the well-known 'morphology-density' relation (Dressler 1980). In addition to these baryonic processes there are other mechanism that can change the properties of the galaxies in different environments. The relation between dark matter perturbations in background and the distribution of dark matter halos (that host galaxies), which is known as the halo bias parameter, play a crucial role in the properties and mass distribution of the galaxies. To understand the influence of environment on galaxy formation, most of the previous studies have focused on the properties of galaxies in high-density regions (e.g. Scarlata et al. 2007; Bower et al. 2008) and few studies have focused on field and void galaxies (e.g. Pustilnik et al. 2002; Rojas et al. 2004; Goldberg et al. 2005; Hoyle et al. 2005, 2012; Kreckel et al. 2012; Pan et al. 2012). In this letter, we consider the other extreme case and study the influence of environment on galaxies which reside mainly in the under-dense or void regions. Since there are no complex processes such as close encounters and galaxy mergers in void regions, void galaxies are excellent probes of the effect of environment and cosmology on structure formation and galaxy evolution

Early spectral and photometric studies of void galaxies have shown that they are statistically bluer, have a later morphological type and higher specific star formation rates than galaxies in average-density environments (Rojas et al. 2004, 2005; Patiri et al. 2006). Recent, high-quality spectroscopic and photometric data from large redshift surveys, and also modern N-body simulation can provide valuable information on void regions (Martel & Wasserman 1990; van de Weygaert & van Kampen 1993; Aragon-Calvo & Szalay 2013; Jennings et al. 2013; Sutter et al. 2012, 2014b; Tavasoli et al. 2013). The unique properties of void environments and their internal structures are appropriate tools for the study of cosmological models (Lavaux & Wandelt 2010; Biswas et al. 2010; Ceccarelli et al. 2013), putting constrains on cosmological parameters (Betancort-Rijo et al. 2009), testing theories of dark energies (Bos et al. 2012; Sutter et al. 2014a) and modified gravity (Clampitt et al. 2013).

In this study, we focus on the photometric properties of void galaxies in various under-dense regions drawn from Sloan Digital Sky Survey (SDSS DR10). We use 1014 void galaxies which reside in 167 voids that are characterized by their luminosity density contrasts.

An important question is whether the formation of void galaxies is in anyway determined by the properties of the host voids. We attempt to address this issue by separating the void galaxies located in more under-dense regions, which we refer to as *sparse voids* from those that reside in denser regions referred to as *populous voids*. We define 'sparse void' $\delta_s = \delta < -0.95$ and 'populous void' $\delta_p = \delta > -0.87$, the motivation for which is discussed in the Section 3. We describe the observational data and sample selection in Section 2. The properties of the void galaxies are discussed in Section 3. A summary and concluding remarks are presented in section 4.

Throughout this paper, we assume a flat ΛCDM cosmology and adopt following cosmological parameters: the Hubble parameter H=70 $\mathrm{km\,s^{-1}\,Mpc^{-1}}$ and the matter density

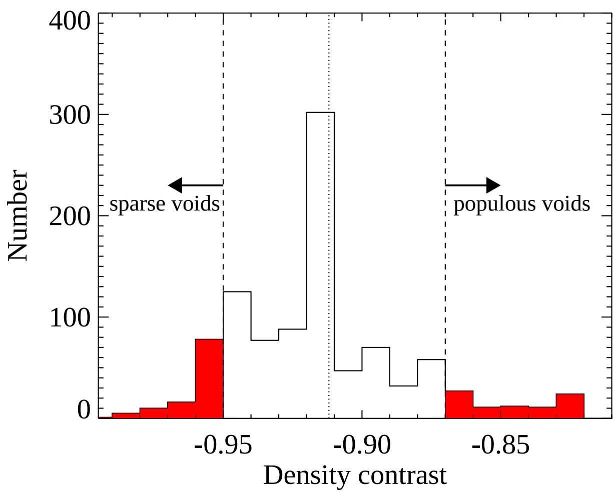

FIG. 1.— The distribution of density contrast of void galaxies. The dotted and dashed lines marks the mean and 1-σ of the distribution, respectively. The two filled regions in the left and right side of the histogram present 'sparse sample' and 'populous sample', respectively. There are 20 of void galaxies with contrast density higher than -0.81 not shown in this figure.

$\Omega_m = 0.27$ (Hinshaw et al. 2013).

2. SAMPLE SELECTION

To study the effect of under-dense environment on formation and evolution of void galaxies, we use a catalog of voids extracted from a volume-limited spectroscopic sample of SDSS DR10 (Ahn et al. 2014) using the method described in Tavasoli et al. (2013).

The boundaries of the selected region of SDSS are $135° <$ RA $< 235°$ and $0 <$ DEC $< 55°$ which contains ~ 66000 galaxies with a limiting r-band magnitude of $m_{r,\mathrm{petrosian}} < 17.77$ up to z ~ 0.055.

The redshift of all selected galaxies are corrected for the motion of the local group and are given in the CMB restframe. Furthermore, the k-corrections of SDSS galaxies are carried out using the KCORRECT algorithm developed by Blanton et al. (2003) and Blanton & Roweis (2007). In order to produce a homogeneous sample of data suitable for the statistical study of void galaxies, we take a volume-limited sample in the redshift range $0.010 < z < 0.055$. The upper limit for the redshift is defined by the limiting magnitude M_r = -19 and leaves $\sim$ 40000 galaxies in the final sample. To extract a void catalog from our SDSS spectroscopic sample, we apply the void finder algorithm introduced by Aikio & Mähönen 1998, which does not require voids to be spherical.

Prior to applying this void finding algorithm, we classified wall and field galaxies based on the distance to the nearest neighbor (Hoyle & Vogeley 2002). Whereas field galaxies are candidate as void galaxies, the AM algorithm starts on the cartesian gridded wall galaxy sample by defining a distance field. To assign each element in the grid sample to a subvoid, we employed the climbing algorithm (Schmidt et al. 2001). Finally, if the distance between two subvoids is less than both distance fields, they will be joined into a larger void. The void volume was estimated using the number of grid points inside a given void multiplied by the volume associated with the grid cell.(see Tavasoli et al. 2013 for further algorithm details).

The generated void catalog, includes variety of voids in size R_v, and luminosity density contrast δ_v. The luminosity density contrast of a void is defined by $\delta_v = (\rho_v - \rho_m)/\rho_m$ where ρ_v is given by the ratio of the total luminosity of galaxies inside a given void by the volume of that void and ρ_m is mean luminosity density of the volume-limited sample. Hereafter, for simplicity, we use density contrast instead of luminosity density contrast. For each void, we defined its effective radius R_v as the radius of a sphere whose volume is equal to that of the void. In order to avoid counting spurious voids in our catalog, the size of voids should be larger than $R_v > 7$ Mpc. Our final catalog contains 167 voids within which 1014 void galaxies, brighter than -19, reside.

3. RESULTS

In this section, we describe general properties of the void galaxies that reside in various under-dense regions.The main aim is to find a connection between the evolution of void galaxies and density contrast of voids. To characterize the environment of void galaxies we attribute the density contrast of each void to all galaxies residing in that void. Fig. 1 presents the distribution of the density contrast associated with 1014 void galaxies identified in 167 voids.

The distribution has a mean of ≈ -0.91 with a standard deviation of 0.04 shown with dotted and dashed lines, respectively. Fig. 1 shows that the under-dense regions where void galaxies reside, have different density contrasts. In order to explore the effect of under-dense regions on the evolution of void galaxies, we define two subclasses of void galaxies according to the density contrast of their host voids: 'sparse void' $\delta_s = \delta < -0.95$ and 'populous void' $\delta_p = \delta > -0.87$. The two classes are defined after rejecting all galaxies within $\pm 1\sigma$ around the mean contrast density. Hereafter we refer to them as 's-sample' and 'p-sample' for simplicity, which represent the void galaxies in sparse and populous voids.There are 110 and 111 galaxies in our s-sample and p-sample located inside 38 and 25 voids, respectively. Based on the definition of void sphericity as given by Tavasoli et al. (2013), the s- and p-voids have average sphericity of 0.71 and 0.69, respectively, with the standard deviation of 0.06 for both samples. Hence, there is no difference between the shape of the voids in two samples. However, the median size of the voids in s-sample, 13 Mpc h^{-1}, is $\sim$ 3 Mpc h^{-1} larger than that of p-sample. The latter will effect the normalisation of the luminosity function (see Fig. 4). In the following subsections we compare photometric properties (luminosity, color and luminosity function) of void galaxies in s- and p-samples to trace the effect of various cosmic environment.

3.1. *Luminosity*

Absolute luminosity is a fine tracer of the total mass of galaxies. Hence, to study the distribution of masses of void galaxies we use their luminosity as a proxy. Unlike overdense regions, it is expected that the probability of finding massive halos in void region to be small. Lack of merger events can be a logical explanation of such observations.

Fig. 2 presents the distribution of the r-band absolute magnitude of void galaxies measured from Petrosian magnitude (Petrosian 1976). The s- and p-samples are drawn using solid and dashed lines, respectively. As it can be seen galaxies in the s-sample have a distribution peaked at $\sim$ -19.5 with few galaxies brighter than $\sim$ -21. On the contrary, the p-sample shows a broader distribution that extends to $\sim$ -22. Therefore, voids of higher density contrasts can host significantly brighter (presumably more massive) galaxies than those of lower density counterpart. Using a Kolmogorov-Smirnov (KS) test we find that the probability of the two samples to be

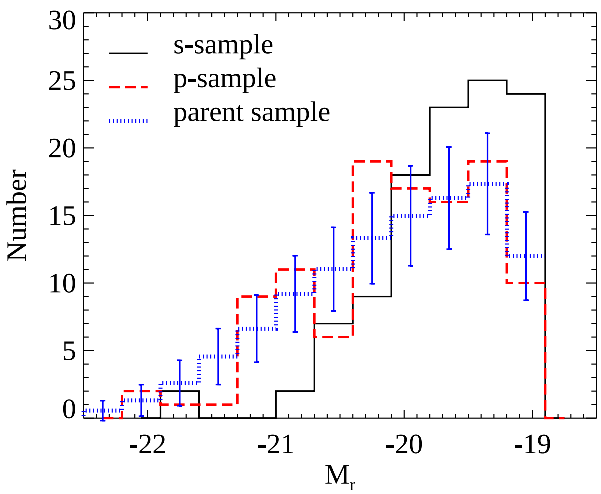

FIG. 2.— The distribution of r-band absolute magnitude of void galaxies. The solid and dashed lines present the distributions for sparse and populous samples, respectively. The dotted line presents the distribution for our parent sample obtained by a Monte Carlo simulation and the errorbars are the standard deviation of each bin (see text for description).

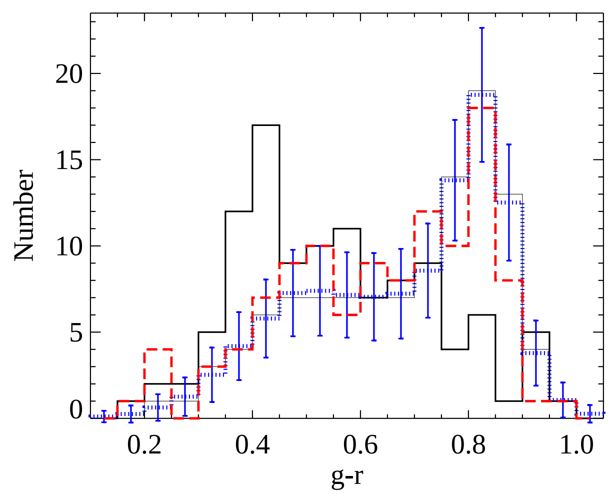

FIG. 3.— The g-r color distribution of sparse and populous void galaxies are shown in solid and dashed lines, respectively. The K-S test shows that the probability of two samples being drawn from similar distribution is only about 0.002. The dotted line presents the distribution for our parent sample obtained by a Monte Carlo simulation and the errorbars are the standard deviation of each bin (see text for description).

drawn from the same parent distribution is negligible (zero). Hence, the difference between the two samples reported here is statistically significant. We further check how different are these two samples in comparison with our parent sample (39750 galaxies) from which we have extracted our void catalog. This exercise will demonstrate how the void galaxy luminosity distribution may differ from the luminosity distribution of galaxies across the local universe as a whole. To do so, we try a Monte Carlo analysis as following: (1) randomly choose 110 galaxies out of 39750 (2) calculating number of galaxies in each magnitude bin (3) repeating steps (1) and (2) 1000 times (4) and finally finding the mean and standard deviation of the 1000 numbers in each bin. We have chosen 110 galaxies at step (1), to keep the same number of galaxies as those of s- or p-sample. The mean and standard deviation obtained in each bin are shown as dashed-dotted histogram and errorbars in Fig. 2. This analysis shows that the p-sample closely follows the parent distribution. Running a KS test we find more than 80% probability that parent and p-sample to have the same distribution. In stark contrast parent and s-sample present a very different magnitude distributions with a zero percent KS test probability.

Existence of massive object in 'p-sample', might be due to the hierarchical nature of structure formation and/or high efficiency of star formation in their progenitors. This indicates that the formation of void galaxies and their path of evolution can strongly depend on their environmental properties. Discriminating between galaxies in various voids, our results also provide an interesting tool to test the prediction of cosmological dark matter simulations and semi-analytical models.

3.2. *Color*

The color of galaxies can be used to probe their dominant stellar populations and star formation history. Generally bluer galaxies have younger stellar population in comparison with red galaxies. It is also known that blue galaxies are dominated by late types while the red galaxies are dominated by early types (e.g. Strateva et al. 2001).

Within the hierarchical framework of ΛCDM, galaxies assemble their masses over time via different modes. Depending on the physical processes and when they act on shaping the galaxy, the resulting stellar populations can become redder or remain blue through sustained star formation. Since processes like merging and gas accretion are important, environment can strongly regulate the evolution of galaxies. This picture demonstrates why galaxy environment appears to play a key role in controlling the stellar population properties of the galaxies and they are the product of a complex assembly and environment history. Observations of void galaxies selected by different samples show that statistically they are gas rich, blue and late-type disk galaxies (Rojas et al. 2004, 2005; Patiri et al. 2006; Kreckel et al. 2011b; Kreckel et al. 2012).

Here,we investigate the color differences between void galaxies in the sparse and populous samples.This approach allows us to see how galaxy color depends on properties of host voids, δ. To do so, we use the model color $(g-r)$ which is derived from the SDSS model magnitudes. For each galaxy, these are derived from the best fitting de Vaucouleur (de Vaucouleurs 1948) or exponential profiles (Freeman 1970). Fig. 3 shows the color distribution of void galaxies in the range of $\sim 0.2-0.9$. Although both distributions have a wide range of colors, a bimodality is clearly visible. The s- and p-sample present single peak around $g-r = 0.4$ (blue) and 0.8 (red), respectively. Repeating the same Monte Carlo analysis as that in section 3.3 we find a 30% probability that parent and p-sample to be drawn from the same distribution (dotted histogram in Fig. 3).

Although the star formation history of a galaxy is a function of stellar mass, the $g-r$ distribution of void galaxies might include a real evolutionary effect, caused by the dependence of the red and blue void galaxy on the density contrast of a void. In other words, regions with different initial cosmological density fields might result in different galaxy populations,namely *active* or *passive*.

3.3. *Luminosity Function*

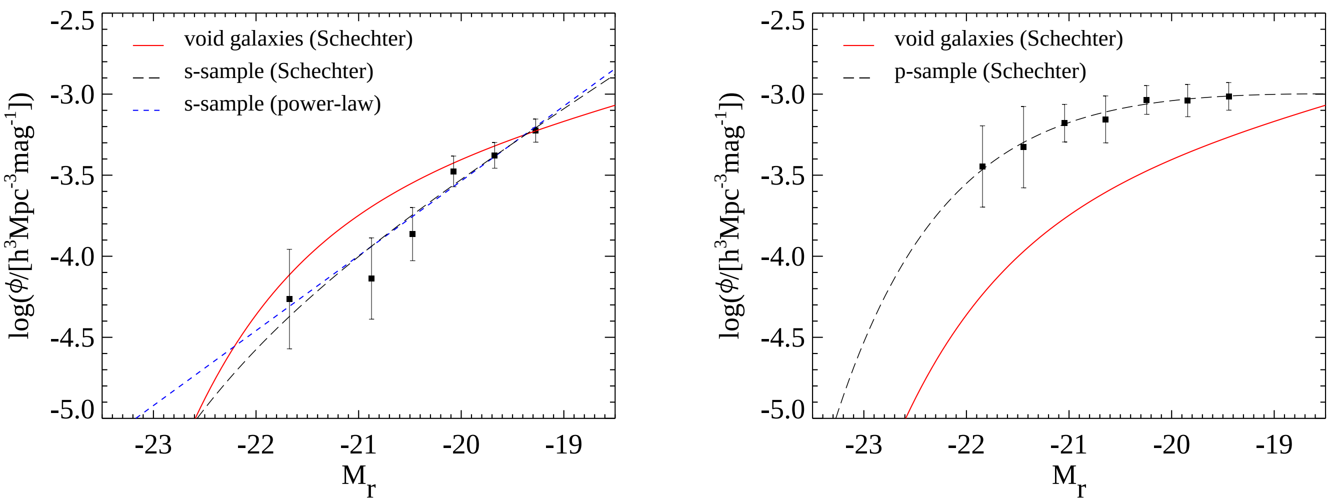

FIG. 4.— *Left:* the LF of s-sample. The long-dashed and dashed lines present the best fitted Schechter and power-law, respectively. *Right:* the LF of p-sample. The long-dashed line presents the best fitted Schechter. The solid line in both panels shows the best fitted Schechter to all 1014 void galaxies. The p-sample galaxies are fitted with a Schechter function while the LF of the s-sample appears to be following a power-law.

TABLE 1
SCHECHTER FITTED PARAMETERS FOR DIFFERENT SAMPLE OF VOID GALAXIES.

samples	α	M^*
all void galaxies	-1.4±0.2	-21.4±0.5
s-sample	-2.0±0.5	-22.5±4.1
p-sample	-0.9±0.5	-21.5±1.3

One of the key statistical tools to study the galaxy distribution is the luminosity function (LF). One can describe the global properties of galaxy populations and study the formation and evolution of galaxies through the LF. To understand how galaxies form, we also need to understand how the LF depends on the environment. The influence of the local environment on the LF from over-dense to under-dense regions (supercluster/void) has been investigated by several authors (e.g. Barkhouse et al. 2007; Bai et al. 2009; Robotham et al. 2010; Zandivarez & Martínez 2011). Although there are many LF studies using different samples and approaches at different redshifts (e.g. Johnston 2011), the majority of them are related to galaxies in over-dense regions. Not many have explored the LF of void galaxies (Hoyle et al. 2005). It is not yet clear how the LF of void galaxies depends on the properties of their host void.

Here we use s- and p-sample to study the LF of void galaxies in different voids, taking the effect of density contrast into account. In Fig. 4 we show the LF of s- and p-sample in the r-band Petrosian magnitude as squared symbols with error bars. We describe the LFs using Schechter function Schechter 1976, which has the following shape

$$\phi(L) = \phi^*(L/L^*)^{\alpha} \exp -(L/L^*) \qquad (1)$$

where α , L^* and ϕ^* are the three parameters to fit. The best fitting LF for different samples are shown in Fig. 4 where the parameters are given in Table 1. Clearly the LF of s-sample does not follow a Schechter function. This can also be inferred from the large errors in the M^* parameters. The large error in the M^* indicate the insensitivity of the LF of the s-sample to this parameters. Further, because the fit passes through 1-σ of all points, the LF of this sample follows a power-law. Fitting a pure power-law we find a power-law index of $\alpha = -2.15 \pm 0.21$ with a reduced χ_ν= 0.54 and. While the χ_ν of power-law is smaller than that of Schechter (χ_ν= 0.70) but the power index of both are consistent within the errors. The LF of all void galaxies as well as that of p-sample are well fitted with the Schechter. The relatively large error in M^* of the p-sample is due to the large errors in its LF which caused by the number statistics.

There are clear differences between the LF of s- and p-sample which is mainly due to the lack of bright galaxies in the sparse sample. Moreover, while the LF of the p-sample follows a Schechter function, it seems like a power-law for the s-sample. Gaussian and double Schechter have been alternatively used to describe the LF of galaxies. Even a cursory look at the LF of s-sample shows a Gaussian would not fit it. Further, fitting a double Schechter which has 6 parameters in the current LF does not seem to be statistically reasonable. Hence, the available data does not allow us to further investigate it. the detailed differences in the shapes of the LF for the two void galaxy samples implies that the possible variety of formation and/or evolution mechanisms are a function of galaxy density even among obvious voids.

4. DISCUSSION

In this paper we have studied the photometric properties of void galaxies based on void catalog on SDSS DR10 at z = 0.010 – 0.055. Our void catalog consists of a large variety of voids from small to large and encompasses a range in density contrast from low to high population. In order to investigate how the density contrast of voids, affects the evolution of void galaxies, we define two subsample of void galaxies which are located in sparse and populous voids. Our results indicate that the two populations show systematic differences in photometric properties such as luminosity, color distribution and the luminosity function. While the luminosity distribution of galaxies in populous voids follows the luminosity distribution of the general population of galaxies in SDSS within $0.010 < z < 0.055$, the luminosity distribution of galaxies in sparse voids show that they are generally dimmer. Also the colors of galaxies residing in sparse voids are bluer and the galaxy generally less luminous indicating that they are likely to have low but sustained rates of inefficient star formation throughout their evolution.

Furthermore, the LF of galaxies in sparse voids do not follow a Schechter function, seen in the populous void galaxies. In this letter we have shown clear indications that the voids with different density contrasts also host different galaxy populations.What is also quite interesting is the similarity between the properties (luminosity, color and LF) of galaxies in populous voids and the general population of galaxies in the local universe. It is not unimaginable that sparse voids could be the least evolved voids in the context of hierarchical structure formation (Sheth & van de Weygaert 2004). Based on this indicative study, one could argue that populous voids contain a mixed population of galaxies which might be the consequence of mergers among voids, contrary to the sparse voids which seem to present a more homogeneous galaxy population.

The purpose of this study was to highlight the important role of the density contrast, specially at the extreme low density environments of the voids, s-sample. Now, having shown that the properties of galaxies depend on whether or not a void is sparse or populous in a non-trivial way, it is important to determine why some voids are sparse and some are populous to truely understand how environmental density affects galaxy evolution and what processes regulate this evolution.

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