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

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ABSTRACT

The influence of underdense environments on the formation and evolution of galaxies is studied by analyzing the photometric properties of ~200 galaxies residing in voids, taken from our Sloan Digital Sky Survey (SDSS) DR10 void catalog up to \( z \approx 0.055 \). We split void galaxies into two subsamples based on the luminosity density contrast of their host voids: “sparse void” \( \delta_v = \delta < -0.95 \) and “populous void” \( \delta_v = \delta > -0.87 \). 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 true for sparse voids. Our analysis suggests that the properties of a host void play 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.

Key words: cosmology: observations – galaxies: formation – galaxies: luminosity function, mass function – large-scale structure of universe

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 overdense regions of “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 high-density regions tend to be redder and earlier type, have lower star formation rates, 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 mechanisms 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 a few studies have focused on field and void galaxies (e.g., Peeples 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 that reside mainly in the underdense 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 from modern N-body simulations, can provide valuable information on void regions (Martel & Wasser蔓man 1990; van de Weygaert & van Kampen 1993; Sutter et al. 2012, 2014b; Aragon-Calvo & Szalay 2013; Jennings et al. 2013; Tavasoli et al. 2013). The unique properties of void environments and their internal structures are appropriate tools for the study of cosmological models (Biswas et al. 2010; Lavaux & Wandelt 2013; Ceccarelli et al. 2013), putting constraints on cosmological parameters (Betancort-Rijo et al. 2009) and 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 underdense regions drawn from Sloan Digital Sky Survey (SDSS DR10). We use 1014 void galaxies that reside in 167 voids that are characterized by their luminosity density contrasts. An important question is whether or not 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 underdense regions, which we refer to as sparse voids from those that reside in denser regions referred to as populous voids. We define “sparse void” as \( \delta_v = \delta < -0.95 \) and “populous void” as \( \delta_v = \delta > -0.87 \), 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 \( \Lambda \)CDM cosmology and adopt the following cosmological parameters: the Hubble parameter \( H = 70 \text{km s}^{-1}\text{Mpc}^{-1} \) and the matter density \( \Omega_m = 0.27 \) (Hinshaw et al. 2013).
2. SAMPLE SELECTION

To study the effect of underdense 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 $135^\circ < \text{R.A.} < 235^\circ$ and $0 < \text{decl.} < 55^\circ$, which contains $\approx 66,000$ galaxies with a limiting r-band magnitude of $m_{r, \text{petrosian}} < 17.77$. From our SDSS spectroscopic sample, we apply the void algorithm introduced by Aikio & Mähönen (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 $\approx 40,000$ 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 candidates 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 a variety of voids in size $R_v$ and luminosity density contrast $\delta_i$. The luminosity density contrast of a void is defined by $\delta_i = (\rho - \rho_0) / \rho_0$, where $\rho$ is given by the ratio of the total luminosity of galaxies inside a given void by the volume of that void and $\rho_0$ is the 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 the general properties of the void galaxies that reside in various underdense 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. Figure 1 presents the distribution of the density contrast associated with the 1014 void galaxies identified in 167 voids.

The distribution has a mean of $\approx -0.91$ with a standard deviation of 0.04 shown with dotted and dashed lines, respectively. Figure 1 shows that the underdense regions where void galaxies reside have different density contrasts. In order to explore the effect of underdense regions on the evolution of void galaxies, we define two subclasses of void galaxies according to the density contrast of their host voids: “spare void” $\delta_i = \delta < -0.95$ and “populous void” $\delta_i = \delta > -0.87$. 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, respectively. 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 an average sphericity of 0.71 and 0.69, respectively, with a standard deviation of 0.06 for both samples. Hence, there is no difference between the shape of the voids in the two samples. However, the median size of the voids in the s-sample, 13 Mpc $h^{-1}$, is $\approx 3$ Mpc $h^{-1}$ larger than that of the p-sample. The latter will affect the normalization of the luminosity function (LF; see Figure 4). In the following subsections, we compare photometric properties (luminosity, color, and LF) of void galaxies in the s- and p-samples to trace the effects of various cosmic environments.

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 a void region is small. A lack of merger events can be a logical explanation of such observations.

Figure 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 can be seen in the figure, galaxies in the s-sample have a distribution peaked at $\approx -19.5$ with a few galaxies brighter than $\approx -21$. On the contrary, the p-sample shows a broader distribution that extends to $\approx -22$. Therefore, voids of higher-density contrasts can host significantly brighter (presumably more massive) galaxies than those of the lower-density counterpart. Using a Kolmogorov–Smirnov (KS) test, we find that the probability of the two samples drawn from the same parent distribution is statistically significant. We further compare how different these two samples are from our parent sample (39,750 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 follows: (1) randomly choose 110 galaxies out of 39,750, (2) calculate the number of galaxies in each magnitude bin, (3) repeat steps (1) and (2) 1000 times, and (4) finally find 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 the dashed–dotted histogram and error bars in Figure 2. This analysis shows that the p-sample closely follows the parent distribution. Running a KS test, we find more than 80% probability that the parent and p-sample have the same distribution. In stark contrast, the parent
and s-sample present very different magnitude distributions with a zero percent KS test probability.

The existence of massive object in the “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 semianalytical 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 such as 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 why 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, 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). Figure 3 shows the color distribution of void galaxies in the range of $g - r$ from 0.2 to 0.9. Although both distributions have a wide range of colors, a bimodality is clearly visible. The s- and p-samples present single peaks 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-samples are drawn from the same distribution (dotted histogram in Figure 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 galaxies on the density contrast of a void.
are the three parameters to index of power law. Fitting a pure power law, we fitted with a Schechter function, while the LF of the s-sample appears to be following a power law.

In other words, regions with different initial cosmological density fields might result in different galaxy populations, namely, active or passive.

3.3. Luminosity Function

One of the key statistical tools used to study the galaxy distribution is the 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 overdense to underdense 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 overdense 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-samples to study the LF of void galaxies in different voids, taking the effect of density contrast into account. In Figure 4, we show the LF of the s- and p-samples in the r-band Petrosian magnitude as square symbols with error bars. We describe the LFs using the Schechter function (Schechter 1976), which has the following shape:

\[
\varphi(L) = \varphi^* \left( \frac{L}{L^*} \right)^\alpha \exp \left( - \frac{L}{L^*} \right),
\]

where \( \alpha, L^*, \) and \( \varphi^* \) are the three parameters to fit. The best-fitting LFs for different samples are shown in Figure 4, where the parameters are given in Table 1. Clearly the LF of the 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 \( M^* \) parameter indicates the insensitivity of the LF of the s-sample to this parameter. Furthermore, because the fit passes through 1\( \sigma \) 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 \( \chi_r^2 = 0.54 \). The \( \chi_r^2 \) of the power law is smaller than that of Schechter (\( \chi_r^2 = 0.70 \)), but the power index of both are consistent within the errors. The LFs 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 is caused by the number statistics.

There are clear differences between the LF of s- and p-samples, 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 the s-sample shows that a Gaussian would not fit it. Furthermore, fitting a double Schechter that has six parameters in the current LF does not seem to be statistically reasonable. Hence, the available data do not allow us to further investigate it. The detailed differences in the shapes of the LF for the two void galaxy samples imply 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 the void catalog of 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 subsamples of void galaxies that 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 LF. 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 shows that they are generally dimmer. Also, the colors of galaxies residing in sparse voids are bluer, and the galaxy is generally less luminous, indicating that they are likely to have low but sustained rates of inefficient star formation throughout their evolution.

Furthermore, the LFs of galaxies in sparse voids do not follow a Schechter function, as seen in the populous void galaxies. In this Letter, we have shown clear indications that 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 that might be the consequence of mergers among voids, contrary to the sparse voids that seem to present a more homogeneous galaxy population.

The purpose of this study was to highlight the important role of the density contrast, especially 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 truly understand how environmental density affects galaxy evolution and what processes regulate this evolution.

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