The Effect of Environment on AGN Activity: The Properties of Radio and Optical AGN in Void, Isolated, and Group Galaxies

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Received 2020 February 13; revised 2020 August 9; accepted 2020 August 14; published 2020 October 28

Abstract

The evolution of galaxies depends on their environment. In this work, active galactic nucleus (AGN) activity in different environments has been studied. The fractions of radio and optical AGN in four different environments have been compared using samples of void, isolated, group member, and the brightest group galaxies. Galaxies in voids show significantly lower stellar ages, concentrations, colors, and surface mass densities, and they experience more one-on-one interactions compared to the isolated galaxies and galaxies in groups. To study pure environmental effects, the biases caused by the stellar mass and galaxy type quantified by 4000 Å break strength have been removed. While the results confirm no dependence of the optical AGN activity on environment in blue galaxies and with lower significance in green galaxies, a higher fraction of optical AGN has been observed for the massive red galaxies in voids compared to the galaxies in dense environments. This may be related to the higher amount of one-on-one interaction observed in the void galaxies, or it may reflect more fundamental differences in the host galaxies or environments of the voids. The radio-mode AGN activity increases in the dense environment for red galaxies. No changes in the radio-loud AGN fraction have been observed for the blue and green galaxies. This shows that the effect of environment on AGN activity is not significant in the presence of cold gas in galaxies. We also discuss whether the efficiency of gas accretion depends on the properties of the host galaxy.

Unified Astronomy Thesaurus concepts: Active galaxies (17); AGN host galaxies (2017); Galaxy interactions (600); Radio active galactic nuclei (2134)

1. Introduction

The supermassive black holes (SMBH) at the heart of massive galaxies play an essential role in the evolution of galaxies and their environments. SMBHs with substantial gas accretions construct active galactic nuclei (AGN), which send a huge amount of momentum and energy into the intergalactic medium (IGM) in the form of radiation, outflows, and jets. The imprint of this activity is displayed in the entire electromagnetic spectrum from radio waves to gamma-rays, and it is widely used for the identification of AGN. The AGN can be selected via the detection of specific optical emission lines as optical AGN or via the detection of powerful radio jets as radio-loud AGN.

There are two major classifications for AGN: they are classified into radiatively efficient (quasar-mode) and radiatively inefficient (radio or jet-mode) based on their accretion rates into the SMBHs, and are classified into radio-loud and radio-quiet based on their radio luminosities. A significant fraction of the radio-loud AGN population is radiatively inefficient, while radio-quiet AGN detected in optical wavelengths display two modes of accretion rates. The host galaxies of AGN in each class are also different. Quasar-mode AGN activity is observed in blue star-forming galaxies, while radio-mode AGN activity is dominant in massive elliptical galaxies with old stellar populations. The origin of the quasar/radio-mode dichotomy is well-explained by the fueling mechanism of the SMBH. The fresh cold gas in blue galaxies is accreted at a high rate in quasar-mode AGN, while the huge reservoir of hot IGM gas in the environment of red elliptical galaxies, accreted slowly to the center, feeds radio-mode AGN; see Heckman & Best (2014) for a review. In contrast, the origin of the radio-loud/radio-quiet dichotomy is still unknown, but the black hole spin may be responsible (Garofalo et al. 2010; McNamara et al. 2011).

In addition to the host galaxy properties, the environments of AGN have also been studied to find a possible connection between AGN activity and the close or large-scale environments. This has been explored for AGN samples selected in various electromagnetic wavelengths. In this regard, quite different results have been obtained, variously reporting enhancement, decrease, or no change in AGN activity at dense environments (Miller et al. 2003; Kauffmann et al. 2004; Gilmour et al. 2007; Bradshaw et al. 2011; Malavasi et al. 2015; Manzer & De Robertis 2014; Koulouridis et al. 2018). The discrepancies in the results are likely to be caused by fundamental differences in powering AGN at different wavelengths (as discussed above); differences in definitions of AGN activity (Man et al. 2019) and environment; or by the possible biases in the samples of AGN, which compare different environments. The latter suggests that these results need to be studied for different types of galaxies because AGN activity has been shown to be a strong function of host galaxy properties, such as mass or color (Best et al. 2005a; Janssen et al. 2012), and host galaxy properties are strong functions of environment (Balogh et al. 2004; Baldry et al. 2006).

The optical AGN activity for galaxies of different types has been investigated in some recent works. Argudo-Fernandez et al. (2018) showed an enhancement in the fraction of AGN with denser environments in quenched isolated galaxies. In a similar study, using samples of early- and late-type galaxies, Lopes et al. (2017) argued that AGN favored environments with lower relative velocities, such as fields, poor groups, and cluster outskirts. In contrast, Sabater et al. (2015) used a sample of galaxies matched in their masses and specific star formation rates (sSFRs), and showed that the effect of environment on the
prevalence of optical AGN activity and luminosity is not significant. All of these studies show that the role of environment on optical AGN activity is still challenging to discern based on the literature.

Previous studies have shown that the radio-mode AGN activity strongly increases in dense environments (Best et al. 2007; Sabater et al. 2013; Malavasi et al. 2015). This result is based on samples that include mostly red and quenched galaxies. Janssen et al. (2012) studied galaxies of different colors and show that, although the radio AGN are dominant in red galaxies, the presence of cold gas in blue galaxies enhances the AGN fraction. Therefore, for radio-mode AGN activity, the effect of the environment needs to be investigated for different types of galaxies.

In addition to the biases caused by the host galaxy types, the definition of environment may also influence the results. Different environmental properties have been used to measure the level of galaxy interaction, such as: local density or overdensity defined based on the 4th nearest neighbor (Man et al. 2019) or on the projected two-point cross-correlation function (Wang & Li 2019); number of galaxies within a specific radius (Malavasi et al. 2015); the level of tidal interaction (Sabater et al. 2013); galaxies in field, void galaxies, and isolated galaxies versus galaxies in pairs, groups, clusters, filaments, and walls (Von Der Linden et al. 2007; Manzer & De Robertis 2014; Argudo-Fernandez et al. 2016; Argudo-Fernandez et al. 2018; Magliciocchetti et al. 2018; Amiri et al. 2019); galaxy group richness or halo mass (Li et al. 2019); the distance to the center of galaxy group or galaxies in the core versus outskirts (Pimbblet et al. 2013; Lopes et al. 2017; Gordon et al. 2018); group luminosity gap (Miraghaei et al. 2014, 2015; Khosroshahi et al. 2017); and status as a merging or non-merging system (Hong et al. 2015).

The main goal of this work is to study both the radio and optical AGN activity in different environments to find out how the interaction of the host galaxy with the environment affects the accretion into the central black hole. Samples of galaxies with different colors are used to remove the bias caused by the galaxy type. The Sloan Digital Sky Survey seventh Data Release (SDSS DR7; York et al. 2000) is used to construct four samples of galaxies in different environments: (i) galaxies in voids, (ii) isolated galaxies, (iii) galaxies in groups, and (iv) the brightest group galaxies (BGGs). They are listed from the lowest to the highest levels of galaxy interaction. Cosmological voids have the lowest environmental density in radii up to tens of Mpc, and the brightest group galaxies are normally located at the center of groups and clusters as the most overdense regions formed in hierarchical galaxy formation. A comparison between different definitions of environment has been performed using the environmental properties defined in the literature and the different environments used in this work.

This paper includes an investigation of various optical properties of galaxies at different environments—including the cosmological voids, as the most underdense regions in the universe. Previous studies have shown galaxies in voids to be fainter (Hoyle et al. 2005), relatively bluer, and more disk-like (Rojas et al. 2005; Ricciardelli et al. 2017) than non-void populations of galaxies. Kreckel et al. (2012) show that void galaxies with ongoing gas accretion are still in the process of assembling. In contrast, galaxies in dense environments are preferentially early-type and red (Balogh et al. 2004). These differences are interpreted as a direct effect of the environment on galaxy evolution. Galaxies in low-interaction environments have shorter merger histories and thus slower evolution. We particularly distinguish between galaxies in voids and isolated galaxies, and we make a comparison between these two types of noninteracting galaxies. The optical AGN activity of noninteracting galaxies has also been investigated by different authors. Amiri et al. (2019) show no enhancement in the fraction of galaxies hosting optical AGN in voids compared to galaxy groups. Argudo-Fernandez et al. (2016) show similar results using samples of isolated and isolated pair galaxies. In contrast, Constantin et al. (2008) show that optical AGN are more common in voids than walls. In this study, both the optical AGN activity and the radio-mode AGN activity in voids are investigated, and the results have been compared with those for group galaxies and isolated galaxies.

The layout of this paper is as follows. The galaxy and radio source samples and the environmental parameters are presented in Section 2. Optical and radio AGN classifications are described in Section 3. The overall properties of each galaxy sample are shown in Section 4. The dependence of AGN activity on the stellar mass and color is investigated in Section 5. The radio and optical AGN activity are shown in Section 6. A summary and conclusions are presented in Section 7. Throughout the paper, we assume a $\Lambda$CDM cosmology with the following parameters: $\Omega_m = 0.3$, $\Omega_L = 0.7$, and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$.

2. Sample Selection

The galaxy sample is based on the “main galaxy sample” of the SDSS DR7 (York et al. 2000; Strauss et al. 2002; Abazajian et al. 2009). The optical spectra were drawn from the value-added spectroscopic catalogs produced by the group from the Max Planck Institute for Astrophysics and Johns Hopkins University (MPA-JHU; see Brinchmann et al. 2004), which provides 818,333 unique galaxy spectra up to the redshift $z = 0.7$. Best & Heckman (2012) combined spectroscopic data from the “main galaxy sample” with radio data from the National Radio Astronomy Observatory Very Large Array (VLA) Sky Survey (NVSS; Condon et al. 1998) and the Faint Images of the Radio Sky at Twenty centimetres (FIRST) survey (Becker et al. 1995) to derive the largest SDSS radio catalog of galaxies with their optical spectra (Best et al. 2005b). This includes total stellar mass and black hole mass (Kauffmann et al. 2003b), 4000 Å break strength (stellar age), galaxy magnitude, color (rest-frame $g-r$), half-light radius as a galaxy size that is a radius containing 50% of the galaxy light ($R_{50}$), concentration ($C = R_{90}/R_{50}$), half-light surface mass density ($\mu_{50} = 0.5 M_*/(\pi R_{50}^2)$), 1.4 GHz total and core radio luminosity, radio size, and morphological classifications (see Miraghaei & Best (2017) for details). The black hole mass has been calculated from the relation between the velocity dispersion ($\sigma_v$) of the galaxy and the black hole mass given in Tremaine et al. (2002): $\log(M_{BH}/M_\odot) = 8.13 + 4.02 \log(\sigma_v/200 \text{ km s}^{-1})$. However, velocity dispersion estimates lower than about 70 km s$^{-1}$ are not reliable, given the SDSS instrumental resolution for the spectra and the low ($S/N$) in this range. This leads to a cut at $\log(M_{BH}/M_\odot) \sim 6.3$ for black hole masses in this study.

The SDSS group catalog has been drawn from Tago et al. (2010) volume-limited group samples. Tago et al. used a modified friends-of-friends (FOF) algorithm to build five sets of galaxy groups with the various absolute magnitude limits for group members in the $r$ band, based on the SDSS magnitude limitation ($r < 17.77$). We adapted the subset of $M_r \leq -20.0$ ($M_r - 5 \log(h) \leq -20$), which is a complete volume-limited
sample of galaxy groups up to the redshift $z = 0.1$. The catalog provides isolated galaxies as galaxy groups with richness $N = 1$. In this study, the galaxy group sample is defined by selecting those with $N \geq 2$.

The sample of galaxies in voids is based on the Pan et al.’s (2012) void catalog, which provides 1054 statistically significant cosmic voids from the SDSS DR7 with radii $>10 \, \text{hr}^{-1} \, \text{Mpc}$ and a median effective radius of $17 \, \text{hr}^{-1} \, \text{Mpc}$ up to $z = 0.1$. There are 8046 galaxies located in voids, with an absolute magnitude limit of $M_r = -20.0$ or brighter, which is required for this work. The void galaxies have been cross-matched with the parent galaxy sample in this study using the SDSS unique Plate, MJD, and Fiber IDs. The overlapping galaxies between the group/isolated samples and the void sample have been classified as void galaxies, which were 593 group member galaxies including 393 BGGs and 7453 isolated galaxies. These were excluded from the isolated, group member, and BGG samples, and were instead labeled as voids. In total, the galaxy sample includes 8046 void galaxies, 61,155 isolated galaxies, 15,842 BGGs, and 46,181 group member galaxies. The final number of galaxies in each class is listed in Table 1.

The environmental parameters introduced by Sabater et al. (2013) have been added to this study. They are available for the SDSS DR7 main galaxy sample in the redshift range $0.03 < z < 0.1$ that is compatible with the galaxy sample in this work. The primary parameters are: (a) the local density, defined as

$$ \eta = \log \left( \frac{3k}{4\pi r_k^3} \right), $$

where $r_k$ is the projected-distance (in Mpc) to the $k^{th}$ nearest neighbor with $k = 10$; and (b) the tidal interaction, defined as the relative tidal forces exerted by companions with respect to the internal binding forces of the target galaxy, and calculated using the equation

$$ Q = \log \left( \sum_i \frac{L_i}{L_{\text{r}}} \left( \frac{2R}{d_i} \right)^3 \right), $$

where $R$ is the estimated radius of the target galaxy, $d$ is the distance between the target and the companion $(i)$, and $L_i$ is the luminosity in the $r$ band. In general, there is a correlation with a large scatter between these two parameters, which means that a galaxy in a dense environment also experiences a large tidal force. The correlation can be removed using principal component analysis (PCA), making a new orthogonal set of parameters. Based on the PCA, Sabater et al. (2013) use a combination of these parameters to define PCA1 and PCA2 as a non-correlated set of environmental parameters that trace the overall interaction level and one-on-one interaction, respectively. PCA1 has positive contributions of density and tidal interaction, and PCA2 has negative contribution of density and positive contribution of tidal interaction. Sabater et al. (2013) also define a second set of environmental properties based on the PCA for group member galaxies using the richness parameter provided by Tago et al. (2010) as PCA1r, PCA2r, and PCA3r via combination of density, tidal interaction, and richness. Similar to the first set of parameters, PCA1r has positive contributions of all three parameters, while PCA2r has positive contribution of tidal and negative contributions of the other two parameters. PCA3r is composed of the positive contribution of richness and the negative contributions of the rest. All of these sets, which are available publicly, are used in this study to quantify the level of interaction in each set of galaxies.

### 3. AGN Classification

AGN have been selected based on their radio power and optical emission lines properties. This defines two samples of radio-mode and optical AGN available in this study.

The optical AGN have been selected based on the BPT diagnostic diagram (Baldwin et al. 1981; Kauffmann et al. 2003a) using the ratio of optical emission lines. AGN, star-forming (SF) galaxies, and a population of transition or composite objects (SF/AGN) have been identified via this method (Kewley et al. 2006). In this study, the optical AGN sample has been constructed by combining the objects identified as either AGN or transition. To have a complete sample of optical AGN up to $z = 0.1$, the [O III] emission-line luminosity cut at $10^{4.5} \, L_\odot$ has been applied to the galaxies selected as AGN (Sabater et al. 2015). Therefore, most of the galaxies in the optical AGN sample are Seyfert galaxies.

The radio source classifications as SF or AGN have been drawn from Best & Heckman (2012). They adapted a combination of three different methods based on: (i) 4000 Å break strengths and the ratio of radio luminosity to stellar mass, (ii) the ratio of radio-to-emission-line luminosity, and (iii) the BPT diagram to separate SF galaxies and the AGN. To have a complete sample of radio AGN, the 3mJy flux density limit of the NVSS has been used to calculate the detection limit. This corresponds to a 1.4 GHz luminosity of $9 \times 10^{22} \, \text{W} \, \text{Hz}^{-1}$ at redshift $z = 0.1$. Therefore, the radio AGN sample is complete to this limit up to the highest redshifts in this study. The radio AGN with the total radio luminosity below this limit are excluded from the radio-loud AGN sample. The number of optical and radio AGN selected in this work in different environments are listed in Table 1.

Based on the AGN sample selection criteria described above, the radio and optical AGN samples in this study overlap only in
a few objects. This happens because the O III emission-line cut selects radiatively efficient AGN while the radio-loud AGN population are mostly radiatively inefficient. Therefore, the optical AGN sample presents radiatively efficient radio-quiet AGN and the radio AGN sample presents radiatively inefficient radio-loud AGN.

4. Overall Properties of the Samples

In this section, the general properties of the samples introduced in Section 2 are investigated.

4.1. Host Galaxy Properties

The main properties of the galaxies in each sample are displayed in Figure 1. There are four samples of galaxies: (i) galaxies in voids (blue), (ii) isolated galaxies (green), (iii) galaxies bounded in groups including BGGs (pink), and (iv) BGGs (red). Galaxies in voids have statistically younger stellar populations (lower 4000 Å break strengths) with more disk-like morphologies (lower concentrations). These parameters clearly show the late-type/passive bimodality in the population of galaxies caused by the galaxy evolution. The vast majority of void galaxies are late-type. The BGG and group samples are dominated by passive galaxies. The population of isolated galaxies appears to have the same fraction of each type, shifted slightly toward the passive galaxies. Similarly, galaxies in voids are bluer and have lower surface mass densities compared to the other three samples. These results are consistent with those in the literature (Rojas et al. 2005; Kreckel et al. 2011; Ricciardelli et al. 2017). In contrast, the BGGs—which are optically brighter by definition—are more massive, with higher black hole masses and ratios of black hole to stellar mass higher than those of the isolated and void galaxies. The significance of the differences have been examined by the two-sided Kolmogorov–Smirnov (KS) test (Kolmogorov 1933). Accordingly, differences above the 3σ confidence level satisfy the condition

\[ D_{m,n} > 1.818 \sqrt{\frac{m + n}{m \times n}}, \]

where \( D_{m,n} \) is the maximum difference between the cumulative distributions of the two samples. Here, \( m \) and \( n \) are the sizes of the first and the second sample, respectively. Only differences above this level are reported in this paper.

4.2. Environmental Properties

To quantify the environmental properties of each sample, the distributions of density, tidal interaction, and the PCA parameters are displayed in Figure 2. This allows us to find the differences between the galaxy samples, specifically comparing the environment of the isolated galaxies with the void galaxies and the group galaxies with the BGGs. The density distributions show that the void galaxies are in the most underdense regions, next are the isolated galaxies, and finally the group galaxies or BGGs have the highest-density environments. In terms of tidal interaction, small differences are found between different samples. Group galaxies and the BGGs experience higher tidal forces than isolated or void galaxies. PCA1 is the main PCA component that is in the direction of density–tidal correlation and follows the same behavior as the density does. Therefore, the overall interaction level for the galaxies is the highest in the BGGs and group member galaxies.

Figure 1. Histograms of the optical properties of galaxies. Colors represent galaxies in voids (blue), isolated galaxies (green), galaxies in groups (pink), and BGGs (red).
and is the lowest in void galaxies. This is also confirmed by PCA1r. PCA2, which has negative contribution of density and positive contribution of tidal interaction, includes information in the direction perpendicular to the PCA1. Accordingly, galaxies in voids have the highest PCA2 values. Therefore, despite their surrounding underdense environment, void galaxies still experience tidal forces from one–on–one interactions, probably from their local environments. This might be caused by having few nearby galaxies. It also confirms the results in Kreckel et al. (2011), who show that void galaxies are gas-rich and display the evidence of gas interactions with the environment. The PCA3r parameter further confirms this. Void galaxies, along with galaxies in group and BGGs, have higher PCA3r than isolated galaxies. This may happen because there is a population of poor galaxy groups in voids. The samples show a small difference in PCA2r.

In summary, density, PCA1, and PCA1r, as indicators for overall interaction level, show galaxies in voids to be the lowest interacting galaxies. PCA2 and PCA3r, which are more sensitive to local interactions, show that galaxies in void are still significantly influenced by their nearby neighboring galaxies. Isolated and void galaxies display different environmental properties. Isolated galaxies are located in higher-density regions but they experience lower levels of local interaction than void galaxies. There is no significant difference, on average, between group galaxy members and the BGG, when environmental properties have been accounted for.

4.3. AGN Activity: A General View

The fractions of galaxies hosting radio (left-hand panel) and optical (right-hand panel) AGN in different environments with respect to the stellar mass are shown in Figure 3. The colors are defined as in Figure 1. The fractions are $n/N$ and the error bars are calculated using a Poissonian approach as $\sqrt{n/N}$ where $n$ and $N$ are the number of radio/optical AGN and the total number of galaxies in each stellar mass bin, respectively. A larger stellar mass bin width has been used to increase the S/N for the radio AGN fraction. The plots show the general trend of AGN activity with respect to the stellar mass and environment before removing the biases caused by the galaxy type. The results can be compared with some of the results that have been published in the literature. The fraction of the radio-mode AGN increases significantly with increasing stellar mass. A recent study shows that this fraction reaches as high as 100% for very massive galaxies (Sabater et al. 2019). Galaxies in voids show the lowest AGN fraction. Isolated galaxies have slightly higher radio AGN fraction than void galaxies. Galaxies in groups and the BGGs show the highest level of radio-mode AGN activity. There is only a small difference between the result for the BGGs and the group member galaxies.

The optical AGN activity does not show strong dependence on the stellar mass when different environments are considered. This is investigated further in Sections 5 and 6. The fraction of optical AGN is higher in void galaxies than in isolated and group galaxies. Isolated galaxies have higher fractions of optical AGN activity than galaxies in groups. The same result has been reported by Kauffmann et al. (2004), who detected lower numbers of optical AGN in higher-density environments. In this section, the relation between AGN activity and the host galaxy properties is studied. It is necessary to separate the impact of these properties from the environmental properties on AGN activity to ensure that any dependence of AGN activity on the environment is not biased by them. One major set of properties is displayed in Figure 1, which includes $r$-band magnitudes, stellar masses, black hole masses, and galaxies’ optical sizes ($R_{S0}$). This set indicates how large galaxies are.

5. AGN Activity: Dependence on the Stellar Mass and Color

In this section, the relation between AGN activity and the host galaxy properties is studied. It is necessary to separate the impact of these properties from the environmental properties on AGN activity to ensure that any dependence of AGN activity on the environment is not biased by them. One major set of properties is displayed in Figure 1, which includes $r$-band magnitudes, stellar masses, black hole masses, and galaxies’ optical sizes ($R_{S0}$). This set indicates how large galaxies are.
The other properties, which include 4000 Å break strengths, concentrations, g–r colors, ratio of black hole to stellar mass, and surface mass densities, represent galaxy types. The stellar mass and 4000 Å break strength have been selected from each set of properties, which will be used to construct similar host galaxy samples. The stellar mass has been selected because it is the main property of galaxies and most of the galaxies’ properties are functions of the stellar mass. 4000 Å break strength has been selected since it represents galaxy type bimodality with a wider separation than other properties, such as g–r color. The bimodality in the distribution of 4000 Å break strengths of galaxies is shown in Figure 1. The blue, green, and red galaxies are defined based on the 4000 Å break strength discussed in Janssen et al. (2012) as follows:

:blue galaxies: \[ 4000 \text{ Å break} \leq 1.45 \]
:green galaxies: \[ 1.45 \leq 4000 \text{ Å break} \leq 1.7 \]
:red galaxies: \[ 1.7 \leq 4000 \text{ Å break} \]

In the following, the dependence of AGN activity on the stellar mass and galaxy color, as defined above, will be shown regardless of the galaxies’ environments. This helps us to find how each mode of AGN activity changes with either the stellar mass or color. The potential biases that may be caused by the rest of the properties will then be explored in a fixed stellar mass–color bin.

The fraction of galaxies hosting optical and radio AGN in different stellar mass–color bins are shown in Figure 4. The AGN fraction depends strongly on the stellar mass in either optical or radio AGN. The radio AGN activity shows a steeper dependence on the stellar mass than the optical AGN activity. The color dependence is different in the two types of AGN activity. The fraction of galaxies hosting radio-loud AGN decreases from red to blue galaxies, while the opposite trend is found for the optical AGN. The fraction of galaxies hosting optical AGN has a strong dependence on color, which shows that optical AGN activity depends on the availability of cold and dense gas in galaxies (Heckman & Best 2014). The radio-mode AGN activity is higher in the red galaxies than in the blue and green galaxies—however, there is an increase in the fraction of radio AGN for massive blue galaxies. This result is consistent with the results of Janssen et al. (2012), showing the low-excitation radio galaxies to have radio luminosities greater than \(10^{23} \text{ W Hz}^{-1}\). The prevalence of radio-mode AGN activity in red galaxies is due to the abundant supply of hot gas from their surrounding environments to the SMBHs. The hot X-ray gas detected in galaxy groups and clusters is the fueling source...
of radio AGN. Red galaxies, which are mostly found in dense environments (e.g., galaxy groups and clusters), are expected to be fed by this gas. This will be investigated in more detail in the following section.

In addition to the stellar mass and color, the dependence of AGN activity on the black hole mass is also strong (Best et al. 2005a; Ishibashi et al. 2014; Barišić et al. 2017). By fixing the stellar mass and color, the variations of other properties such as the black hole mass have been investigated for galaxies of different environments (Figure 5). This allows us to find out all the potential biases in the samples, which may influence AGN activities. The plots show the mean value of each parameter. Blue, green and red galaxies are presented by solid, dotted, and dashed lines, respectively. Galaxies in voids (blue), isolated galaxies (green), group galaxies (pink), and BGGs (red) are shown in different colors. The error bars show the standard deviation of the mean.

There is a strong correlation between the black hole mass and the stellar mass in all types of galaxies (Figure 5(e)). Figure 5(e) omits the mean values of the black hole masses for the stellar mass bin of \(M_\ast \sim 10^{10.2} M_\odot\) for the red, blue, and green galaxies, as well as the stellar mass bin of \(M_\ast \sim 10^{10.5} M_\odot\) for the blue and green galaxies. This happens because the number of objects with unreliable black hole masses (\(M_\text{BH} < 10^{6.3} M_\odot\)) is significant in the low stellar mass bins, thus the mean values are uncertain. In red galaxies, the concentration (Figure 5(d)) and surface mass density (Figure 5(h)) show only a little evolution as the stellar mass increases, while these parameters significantly increased for blue and green galaxies. It is well-illustrated by this plot that if the stellar mass and color are fixed for blue (solid) and green (dotted) galaxies, then other host galaxy properties, including the black hole mass, do not change significantly in response to the environment being changed. In red (dashed) galaxies, the void sample galaxies in the high stellar mass bins have on average lower concentrations (Figure 5(d)), lower black hole masses (Figure 5(e)), and lower ratios of black hole to stellar mass (\(\sim 5\sigma\); Figure 5(f)). This may influence the results in Section 6. There are high scatters in the lowest and the highest mass bins, due to the small number counts. Therefore, substantial care should be taken in interpreting the results in these bins. The mean value of the stellar mass and 4000 Å break in each stellar mass–color bin (not presented in Figure 5) are matched well for all types of environment.

6. AGN Activity and Galaxy Environment

In this section, AGN activity will be investigated for samples of galaxies with different environments and in fixed stellar mass–color bins. The fraction of galaxies hosting AGN with respect to the stellar mass are plotted for galaxies of different colors and environments in Figure 6. The upper panels show optical AGN activity, and the lower panels show the radio-mode AGN activity. The blue, green, and red galaxies are presented with solid, dotted, and dashed lines, respectively—as in Figure 5. The colors indicate different environments as defined in Figure 1. The optical AGN activity in the blue galaxies does not show any dependence on the environment. The green and red galaxy samples show the same results with a lower S/N due to the smaller AGN sample size. The only exceptions are in the lowest mass bin for green BGGs and the highest mass bin for the red void galaxies. For the former, it is worth noting that the BGGs in the lowest mass bin mostly belong to small groups of two members, corresponding to a very low halo mass, and so the group identification uncertainty is high in this stellar mass bin. Therefore, a possible explanation is a random error due to the small sample size in this bin. Figure 5(d) shows that the mean of concentration is slightly lower for green BGGs in \(M_\ast \sim 10^{10.5} M_\odot\), which may also influence the observed difference there. For the latter, in the red void galaxies in \(M_\ast \sim 10^{11.4} M_\odot\), Figure 5(d) shows a significant decrease in the concentration index of galaxies in voids compared to the galaxies in groups and in the BGG sample. An increase in the fraction of optical AGN in the highest stellar mass bin is also seen in Figure 3 (right-hand panel), therefore the difference is not a random fluctuation.

To investigate whether the bias from the concentration index causes this difference, optical AGN activity has been estimated for galaxy samples matched in concentration. Red galaxies with different environments in the stellar mass range \(M_\ast \sim 10^{11.2–11.5} M_\odot\) are considered. The black hole mass versus the concentration index for these massive red galaxies is plotted in Figure 7. The colors represent different environments, as in Figure 1. There is a tail of low-concentration void galaxies that have slightly low black hole masses. To select galaxy samples matched in concentration, a division line \(C = 2.8\) is drawn to separate galaxies into two bins of low and high concentrations. The optical AGN activities are then calculated for each bin. The difference between the optical AGN activity of voids and the other three samples has been replicated for each concentration bin. Therefore, the higher fraction of optical AGN in massive void galaxies is not biased by the host galaxy properties. A higher fraction of optical AGN for galaxies in voids is also reported in Constantin et al. (2008). In contrast, Amiri et al. (2019) reported no enhancement in the fraction of galaxies hosting optical AGN in voids compared to galaxy groups.

The radio-loud fractions in the blue, green, and red galaxies are shown in the lower panels of Figure 6. The highest S/N has been reached for the red galaxy samples. The stellar mass–color bins with no error bars indicate there is only one radio source in the entire bin width. The fractions of radio-loud AGN in the red galaxies show strong dependence on the environment. Galaxies in voids as the most underdense regions have the lowest radio-loud fraction. There is no difference between galaxies in groups and the BGGs in the stellar mass bins greater than \(10^{11.5} M_\odot\). The radio-loud fractions in blue and green galaxies show no dependence on the environment. Although the number of void galaxies hosting radio AGN is not sufficient to be compared with the other galaxy samples, the isolated and group galaxies and the BGGs with good statistics show that there is no significant difference between radio-mode AGN activity in different environments for either blue (solid) or green (dotted) galaxies. Larger radio-loud samples of blue and green galaxies, especially in voids, are required to reach a robust conclusion. The radio-mode AGN activity increases in dense environments in red elliptical galaxies, where the hot IGM gas seems to be the only feeding source, while the role of environment is not significant in blue and green galaxies, in the presence of cold gas as a dominant source of feeding for the SMBH.

Combining the results of optical and radio AGN shows that the environment does not contribute greatly to fueling the SMBH in blue and green galaxies. The effect of environment on AGN activity can be better detected in the absence of cold gas in the red quenched galaxies. In the radio-mode AGN activity, where hot accretion dominates, fueling of AGN from
Figure 5. The y-axis is the mean of each galaxy property. Colors represent galaxy samples with different environments, as in Figure 1. Blue, green, and red galaxies (as defined in Section 5) are presented by solid, dotted, and dashed lines, respectively. Error bars show standard deviation of the mean.
the hot IGM gas may decrease in the presence of cold gas. In other words, the efficiency of hot accretion depends on the host galaxy properties. In optical AGN activity, the SMBHs are assumed to be fed mainly by the star-forming cold gas that is available inside the galaxies or brought through filaments in the local environment of the galaxies. Therefore, the effect of environment can be better seen in the red galaxies, where there is usually little-to-no cold gas. In this regard, it is shown that massive void galaxies have a significantly higher fraction of optical AGN. This can be considered as direct evidence for the effect of environment on optical AGN activity because void galaxies experience a higher level of one-on-one interaction, which is trivially more pronounced in the massive galaxies. A more fundamental reason related to the formation and evolution of galaxies in voids may also be responsible for this, which indirectly confirms the effect of environment on optical AGN activity.

7. Summary and Conclusion

In this study, the radio and optical AGN activities of galaxies in different environments have been investigated. Samples of galaxies in groups, BGGs, and isolated galaxies from Tago et al. (2010), along with a sample of galaxies in voids from Pan et al. (2012), have been used for this aim. The combined radio and optical data of galaxies, including the SDSS value-added spectroscopic catalog adapted from Best & Heckman (2012), are also used to extract the galaxy properties. The environmental parameters have been drawn from Sabater et al. (2013).

The galaxy samples display different host galaxy and environmental properties. The void samples have a higher fraction of late-type and blue star-forming galaxies than the other three samples. The BGG and galaxy group samples have higher fractions of early-type, red, and quenched galaxies than the isolated galaxy and void galaxy samples. The environmental parameters show that galaxies in voids have the lowest-density environment, and the isolated galaxies, group galaxies, and the BGGs show increasingly higher-density environments, in that order. In terms of one-on-one interaction, it is shown that galaxies in voids have the highest level of interaction.

To find the effect of environment on AGN activity, the biases caused by the host galaxy properties have been removed. Both the radio-mode and optical AGN activities show a strong dependence on the stellar mass and color of the host galaxy. Using galaxy samples matched in stellar mass and color, optical and radio-mode AGN activities have been investigated in different environments. No dependence on the environment is found in either optical or radio AGN activity in blue galaxies, nor in green galaxies with lower S/N. The effect of environment on AGN activity is significant in red galaxies.
This implies that the efficiency of gas accretion from close or large-scale environments into SMBHs is low in the presence of cold gas in the galaxies. Red galaxies in dense environments, such as the BGGs and group member galaxies, have higher fractions of radio-loud AGN compared to galaxies in voids and isolated galaxies. Therefore, in the absence of fresh cold gas in the galaxy, the hot IGM gas in a dense environment efficiently triggers radio-mode AGN activity. Massive red galaxies in voids show a higher optical AGN fraction than other galaxy samples. A more detailed investigation was performed to show that, in addition to the stellar mass and color, this result is not biased by the concentration and black hole mass of the host galaxies. The results provide new evidence for the effect of environment on optical AGN activity, which may be due to the higher level of one-on-one interaction in void galaxies, or it may be derived from a more fundamental difference in the formation and evolution of galaxies in voids compared to denser environments.

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