A CROSS-CORRELATION ANALYSIS OF ACTIVE GALACTIC NUCLEI AND GALAXIES USING VIRTUAL OBSERVATORY: DEPENDENCE ON VIRIAL MASS OF SUPERMASSIVE BLACK HOLE

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ABSTRACT

We present results of the cross-correlation analysis between active galactic nuclei (AGNs) and galaxies at redshift 0.1–1. We obtain data of ~10,000 Sloan Digital Sky Survey AGNs in which their virial masses with a supermassive black hole (SMBH) were estimated. The UKIDSS galaxy samples around the AGNs were obtained using the virtual observatory. The scale length of AGN–galaxy cross-correlation for all of the samples is measured to be $r_0 = 5.8^{+0.8}_{-0.6} h^{-1}$ Mpc (for the fixed slope parameter $\gamma = 1.8$). We also derived a dependence of $r_0$ on the BH mass, $M_{\text{BH}}$, and found an indication of an increasing trend of $r_0$ at $M_{\text{BH}} > 10^8 M_\odot$. It is suggested that the growth of SMBHs is mainly driven by interactions with the surrounding environment for $M_{\text{BH}} > 10^8 M_\odot$. On the other hand, at $M_{\text{BH}} \lesssim 10^8 M_\odot$, we did not find the BH mass dependence. This would imply that for less massive BHs, the mass growth process can be different from that for massive BHs.

Key words: astronomical databases: miscellaneous – galaxies: active – large-scale structure of universe – quasars: general – virtual observatory tools

Online-only material: color figures

1. INTRODUCTION

It is thought that most galaxies harbor supermassive black holes (SMBHs) in their centers, and that gas accretion onto an SMBH is the energy source of active galactic nuclei (AGNs; e.g., Richstone et al. 1998; Ferrarese & Ford 2005). There are strong correlations between the mass of an SMBH and the observational properties of its host galaxy such as velocity dispersion and stellar mass of the bulge (e.g., Magorrian et al. 1998; Ferrarese & Merritt 2000).

Growth of the BH mass is strongly coupled to the evolution of the host galaxy, but the process of “co-evolution” is still unknown. It is thought that BHs grow by accretion of gas and/or merger of BHs, but the physical mechanisms of gas inflow toward central regions of galaxies and coalescence of binary BHs are not yet revealed. In the standard hierarchical structure formation framework, major mergers of galaxies should have played important roles for the evolution of galaxies, growth of SMBHs, and AGN activity. Thus, investigating the clustering of the galaxies around AGNs is crucial to understand the evolution of SMBHs and galaxies.

Recent large-scale surveys, such as the Sloan Digital Sky Survey (SDSS), provide observational samples of over 100,000 AGNs (Schneider et al. 2010). The auto-correlation function of AGNs was studied using the SDSS sample (Shen et al. 2007, 2009; Ross et al. 2009). The clustering of galaxies around AGNs in the areas of deep surveys was also investigated by some authors (e.g., Coil et al. 2009; Mountrichas et al. 2009, 2013). They showed that the cross-correlation function between AGNs and galaxies is similar to the auto-correlation of luminous red quiescent galaxies. Hickox et al. (2009) found that radio selected AGNs are strongly clustered, and that infrared selected AGNs are more weakly clustered than optically selected AGNs. Recently, cross-correlation between AGNs and galaxies was studied using large samples. Donoso et al. (2010) computed the cross-correlation between ~14,000 radio-loud AGNs at $z = 0.4–0.8$ and a reference luminous galaxy sample, and compared the clustering amplitude of radio galaxies with that of ~7000 SDSS quasars. They argued that radio-loud AGNs are clustered more strongly than radio-quiet ones. Krumpe et al. (2012) investigated clustering of galaxies around ~3000 X-ray selected AGNs and ~8000 optically selected AGNs at $z < 0.5$. No significant difference was found between X-ray selected and optically selected broad-line AGNs.

In order to understand the interaction between the growth of SMBHs and their surrounding environment, it is important to investigate the dependence of clustering amplitude on physical properties of BHs. Shen et al. (2009) studied the dependence of the two-point auto-correlation function of quasars on luminosity, BH mass, color, and radio loudness, and found weak or no dependence on virial BH mass. The cross-correlation function between AGNs and galaxies will achieve smaller uncertainties in clustering measurement because it has many more pairs at a given separation compared with the auto-correlation function of AGNs. Donoso et al. (2010) found a positive dependence of the cross-correlation amplitude on stellar mass $M_*$, but their sample is radio-loud AGNs within a narrow range of stellar mass $(10^{11} M_\odot < M_* < 10^{12} M_\odot)$. There is no previous study to investigate the dependence of the cross-correlation function between AGNs and galaxies on BH mass over a wide mass range.

In this study, we investigate the dependence of clustering amplitude of galaxies around AGNs on the BH mass to reveal a relation between the mass growth of SMBHs and the large-scale environment of their host galaxies. We have collected observational data of a large number of AGNs and galaxies by using the Japanese Virtual Observatory (JVO),1 and computed the cross-correlation function between AGNs and galaxies. Thanks to the large sample covering a large area of the sky, we were able to perform the clustering analysis in a manner free from the cosmic variance. To investigate BH mass dependence over a wide mass range ($\gtrsim 2$ dex), we also use the sample of less massive BHs by Greene & Ho (2007) in addition to the SDSS quasar catalog (Shen et al. 2011), as described below.

1 http://jvo.nao.ac.jp/portal/
Throughout this paper, we use the following cosmological parameters: $\Omega_M = 0.3$, $\Omega_{\Lambda} = 0.7$, $h = 0.7$. All magnitudes are given in the AB system. All of the distances are measured in comoving coordinates.

2. DATA SETS

The AGN sample was extracted from two catalogs by Shen et al. (2011) and Greene & Ho (2007), both of which contain the estimated virial mass, $M_{\text{BH}}$, of the SMBHs. Shen et al. (2011) derived the virial mass of the BHs for 105,783 quasars in the SDSS DR7 quasar catalog (Schneider et al. 2010). About half of their samples were uniformly selected by the criteria described in Richards et al. (2002), and the remaining samples were selected by a variety of earlier algorithms or serendipitous selections.

Greene & Ho (2007) derived BH masses for $\sim$8500 active galaxies at $z < 0.35$ based on SDSS DR4 spectra. They also analyzed spectra for objects classified as galaxies, not only quasars. They extracted the AGN components from spectra of galaxies and estimated BH masses. Their catalog contains more objects than the sample of Shen et al. (2011) for $M_{\text{BH}} \lesssim 10^7 M_\odot$.

They both estimated the virial mass of BHs by means of the observed FWHM of the emission lines of H$\alpha$, H$\beta$, or Mg ii and the continuum luminosity at the lines. Shen et al. (2011) used H$\beta$ estimates for $z < 0.7$ and Mg ii estimates for $z \geq 0.7$ as a fiducial virial mass estimate but also gave estimates based on other lines in their catalog when the lines were detected. For the samples of Shen et al. (2011), we used their fiducial mass estimate in this paper. Greene & Ho (2007) used H$\alpha$ estimates. We have found that there is a systematic difference of $\sim 0.5$ dex between the virial masses estimated in the two catalogs, mainly because they used different parameter values in the virial mass estimator. Figure 1 shows the estimated mass of 2139 AGNs which are registered in both catalogs. For the samples of Greene & Ho (2007), we have recomputed the virial mass by means of the FWHM and luminosity in Greene & Ho (2007) with the parameter values in Shen et al. (2011) for the H$\alpha$ line. For the recomputed virial mass, the systematic difference is decreased as shown in the bottom panel of Figure 1. The recomputed masses by means of the data of Greene & Ho (2007), however, are still $\sim 0.2$ dex smaller than the estimated masses in the catalog of Shen et al. (2011) on average. Half of this remaining systematic difference is because the FWHM and luminosity values were derived from the H$\alpha$ line for Greene & Ho (2007) but from the H$\beta$ line for Shen et al. (2011). The other half is because Greene & Ho (2007) measured the luminosity and FWHM of the emission lines of the extracted AGN components but Shen et al. (2011) measured the lines without eliminating the host galaxy component from the spectra. However, this difference with $\sim 0.2$ dex does not change our main conclusions as shown later. For the AGNs registered in both catalogs, we use the data in the catalog of Shen et al. (2011).

We used the UKIDSS DR8 Large Area Survey (LAS) catalog (Lawrence et al. 2007) for galaxy samples. For each AGN, the UKIDSS $K$-band data are searched around the AGN coordinates within $1^\circ$. We selected AGN samples of $z > 0.1$ in order to analyze the projected number density as a function of the projected distance $r_p$ within $r_p \lesssim 7$ Mpc in the following. To obtain the data around the sample AGNs, we repeat to search galaxy data in the UKIDSS LAS catalog to the number of the sample AGNs. We obtained the data by accessing the UKIDSS VO service through the JVO command line tools. By means of the VO tools, we can recurrently access large data archives easily. To remove stars from the UKIDSS samples, we selected data for which the merged class flag equals 1 (galaxies) or $-3$ (probable galaxies). We also removed data of poor quality which have post-processing error quality bit flags larger than 255.

The limiting magnitude $m_{\text{limit}}$ of the UKIDSS galaxy samples is estimated for each AGN sample, and the result is plotted in Figure 2. As can be seen from the figure, $m_{\text{limit}}$ distributes around 19.7–20.3. For each AGN, we also estimated the threshold magnitude, $m_{\text{th}}$, below which detection efficiency for galaxies can be regarded as 100%. Figure 3 shows the absolute magnitude corresponding to $m_{\text{limit}}$ and $m_{\text{th}}$ at AGN redshift. The detailed definition of the $m_{\text{limit}}$ and $m_{\text{th}}$ is described in the next section.
Figure 2. Distribution of the K-band limiting magnitude $m_{\text{limit}}$ of the UKIDSS galaxy sample as a function of AGN redshift. Each point denotes $m_{\text{limit}}$ for the area around each AGN sample. A total of 11,335 AGN samples of $z = 0.1–1.0$ are distributed in the survey area of UKIDSS LAS.

Figure 3. Distribution of the K-band absolute limiting magnitude $M_{\text{limit}} = m_{\text{limit}} - DM$ (red crosses) and absolute threshold magnitude $M_{\text{th}} = m_{\text{th}} - DM$ (green circles) of the UKIDSS galaxies around each AGN as a function of AGN redshift. DM is the distance modulus. $m_{\text{th}}$ is a threshold magnitude defined in Equation (7), above which the detection efficiency for galaxies becomes lower than 1.0. AGN samples are the same as in Figure 2.

(A color version of this figure is available in the online journal.)

To remove the data of poor sensitivity, we adapted selection criteria of $\rho_0 > 10^{-4}$ and $z < 1.0$, where $\rho_0$ is the average number density of galaxies detectable at the AGN redshift. $\rho_0$ was calculated by integrating the luminosity function up to the absolute magnitude corresponding to the apparent limiting magnitude $m_{\text{limit}}$ as described in the next section and Shirasaki et al. (2011). Figure 4 shows the calculated $\rho_0$ as a function of AGN redshift. In the same figure, the number densities of the complete sample (blue) are also shown, and they are calculated by integrating the luminosity function up to the absolute magnitude corresponding to $m_{\text{th}}$. The combined AGN catalog, which is based on catalogs of Shen et al. (2011) and Greene & Ho (2007), lists 32,806 AGNs at redshift between 0.1 and 1.0. A total of 11,335 objects are distributed in the survey area of UKIDSS LAS among them. In Figures 2–4, values for areas within 1° around these 11,335 AGNs are plotted. A total of 10,482 AGNs are selected by the criterion of $\rho_0 > 10^{-4}$ Mpc$^{-3}$ for $m_{\text{limit}}$.

Figure 4. Distribution of the average number density $\rho_0$ of detectable galaxies ($<m_{\text{limit}}$, red crosses) and galaxies brighter than $m_{\text{th}}$ (blue circles) at the AGN redshift for each AGN sample. Among the 11,335 AGN samples plotted in this figure, 10,482 AGNs with $\rho_0 > 10^{-4}$ Mpc$^{-3}$ for detectable galaxies (red crosses above the dashed line) are used in the following analysis. For the analysis of the complete galaxy sample in Section 4.3, we use 6107 AGNs with $\rho_0 > 10^{-4}$ Mpc$^{-3}$ for galaxies brighter than $m_{\text{th}}$ (blue circles above the dashed line).

(A color version of this figure is available in the online journal.)

To reduce the effect of foreground clusters which are accidentally located near the sample AGNs on the sky, we rejected samples with anomalous distribution of surrounding galaxies by the method described in Shirasaki et al. (2011). To reduce the effect of accidental alignment of the foreground cluster, we calculate the clustering coefficient, $B_{\text{OG}}$, around each AGN, which was defined as $\xi(r) = B_{\text{OG}}r^{-\gamma}$ (Barr et al. 2003), where $\xi(r)$ is the cross-correlation function. $B_{\text{OG}}$ is calculated as $B_{\text{OG}} = (3 - \gamma)/(2\pi C(\gamma))(N_{\text{total}} - N_{\text{bg}})/\rho_0$ (1 Mpc)$^{-\gamma-3}$, where $N_{\text{total}}$ is the total number of observed galaxies at $r_p < 1$ Mpc, where $r_p$ is a perpendicular distance, and $N_{\text{bg}}$ is the expected background count at $r_p < 1$ Mpc (see Section 3 for the definition of $\xi$, $r_p$, $\gamma$, and $C(\gamma)$). We reject AGN samples with $|B_{\text{OG}}| > 10^3$ (30 times the clustering coefficient of the Abell class 0 objects). In addition, we select sample AGNs without the effect from the nearby cluster located in regions offset from the AGNs. We count the number density $n(r_p)$ of UKIDSS galaxies for each circular region with $\Delta r_p = 0.2$ Mpc width around AGNs and compute their statistical error. We adopt the following criteria: the reduced $\chi^2$ of the radial number density relative to the flat distribution is $\chi^2/(n-1) \leq 3$; the maximum deviation, $\sigma_{\text{max}}$, of the $n(r_p)$ is smaller than 5σ. In Section 4, we also show the results without these selections for comparison.

We also present results of analysis for the AGN sub-sample whose deviations of surface number density of UKIDSS sources are smaller than 1.5σ at a limiting magnitude $m_{\text{limit}}$ to check again the effect of foreground objects. Figure 5 shows the projected number density, $n(7\text{Mpc})$, of galaxies in the area around the AGN with an angular radius corresponding to 7 Mpc (comoving) at the AGN redshift as a function of $m_{\text{limit}}$. Because the projected number density of the foreground or background galaxies is $\sim$30 times larger than the galaxies in the host clusters even for the highly clustered region with $r_0 \sim 10$ Mpc, this criterion rarely rejects sample AGNs with the real overdensities around them, but rejects AGNs located near the foreground clusters.

We used 9394 AGNs, which were selected by criteria described in Shirasaki et al. (2011), in the following analysis. A total of 8060 AGNs were selected by the 1.5σ criterion for

\begin{align*}
\rho_0(\text{Mpc}^{-3}) &= \frac{N_{\text{total}} - N_{\text{bg}}}{\rho_0(\text{Mpc}^{-3})} (1 \text{ Mpc})^{-\gamma-3}, \\
\chi^2 &= (n-1) \leq 3, \\
\sigma_{\text{max}}(n(r_p)) &= 5\sigma.
\end{align*}
mass estimator in Shen et al. (2011). A total of 3749 objects
we plot the recomputed virial mass using the parameters of
(2011, green circles). For the samples by Greene & Ho (2007),
crosses), and the others were from the catalog of Shen et al.
were extracted from the catalog of Greene & Ho (2007, red
9394 SMBHs as a function of redshift. A total of 1202 AGNs
samples are the same as in Figure 2.

Figure 5. Distribution of the surface number density of galaxies around AGNs as a function of the $K$-band limiting magnitude. $n_{\gamma\text{Mpc}}$ is the surface density of UKIDSS galaxies in the circular area around the AGN within an angular radius corresponding to 7 Mpc (comoving) at the AGN redshift. We select AGN samples whose deviations of log $n_{\gamma\text{Mpc}}$ are less than 1.5$\sigma$ (between the two solid lines) to reject the effect of foreground clusters and bad quality regions of UKIDSS data. AGN samples are the same as in Figure 2.

### Table 1: Statistics of Fitting Parameters for Each Virial Mass and Redshift Group

| Virial Mass log($M_{BH}/M_{\odot}$) | Redshift $n_{AGN}$ | ($\log(M_{BH}/M_{\odot})$)$_g$ | $\langle z \rangle$ | $n_{g}$ | $m_{bg}$ | $\rho_{bg}$ |
|------------------------------------|---------------------|-------------------------------|----------------|---------|---------|---------|
|                                    | 0.1–1.0 9394        | 8.42 0.59 5.810.8 6.5–7.2    | 10.473 ± 0.005 | 1.9 ± 0.4 |
| 9.0–10.0                           | 0.1–1.0 1331        | 9.23 0.72 8.211.6 7.2–8.0    | 4.542 ± 0.008 | 0.93 ± 0.25 |
|                                    | 0.1–0.3 33          | 9.27 0.24 ... 8 7.2–8.0      | ... ...        | ... ... |
|                                    | 0.3–0.6 347         | 9.24 0.48 8.711.0 7.2–8.0    | 7.29 ± 0.02 | 2.0 ± 0.5 |
|                                    | 0.6–1.0 951         | 9.22 0.82 7.011.3 7.2–8.0    | 2.70 ± 0.01 | 0.38 ± 0.15 |
| 8.2–9.0                            | 0.1–1.0 5119        | 8.60 0.66 7.011.2 6.5–7.2    | 6.001 ± 0.005 | 1.3 ± 0.3 |
|                                    | 0.1–0.3 320         | 8.50 0.24 7.311.0 6.5–7.2    | 29.40 ± 0.04 | 5.3 ± 0.9 |
|                                    | 0.3–0.6 1635        | 8.56 0.47 6.511.0 6.5–7.2    | 7.49 ± 0.01 | 2.1 ± 0.5 |
|                                    | 0.6–1.0 3164        | 8.62 0.80 7.611.3 6.5–7.2    | 2.87 ± 0.004 | 0.42 ± 0.16 |
| 7.5–8.2                            | 0.1–1.0 2278        | 7.91 0.44 4.411.0 5.1–6.0    | 15.69 ± 0.01 | 2.8 ± 0.6 |
|                                    | 0.1–0.3 664         | 7.82 0.22 4.511.0 5.1–6.0    | 38.26 ± 0.03 | 5.7 ± 1.0 |
|                                    | 0.3–0.6 967         | 7.92 0.44 4.311.0 5.1–6.0    | 8.53 ± 0.01 | 2.3 ± 0.5 |
|                                    | 0.6–1.0 642         | 8.00 0.75 2.511.8 5.1–6.0    | 3.22 ± 0.01 | 0.53 ± 0.19 |
| 6.5–7.5                            | 0.1–1.0 635         | 7.22 0.25 4.611.0 5.1–6.0    | 38.65 ± 0.03 | 5.4 ± 0.9 |
|                                    | 0.1–0.3 513         | 7.18 0.20 4.811.0 5.1–6.0    | 45.69 ± 0.04 | 6.1 ± 1.0 |
|                                    | 0.3–0.6 101         | 7.36 0.38 ... 6 6.5–7.2      | ... ...        | ... ... |
|                                    | 0.6–1.0 21           | 7.30 0.77 ... 6 6.5–7.2      | ... ...        | ... ... |

Notes.

$^a$ Number of sample AGNs.
$^b$ Average of logarithm of BH mass.
$^c$ Average redshift.
$^d$ Correlation length; the error contains the systematic error due to the uncertainty of $\rho_{bg}$ and the 1$\sigma$ statistical error.
$^e$ Average of the projected number density of background galaxies.
$^f$ Average of the averaged number density of galaxies at the AGN redshift.
$^g$ We do not derive parameters for the sub-sample with $n_{AGN} < 200$.

$n_{\gamma\text{Mpc}}$. Figure 6 shows the distribution of the virial mass of the 9394 SMBHs as a function of redshift. A total of 1202 AGNs were extracted from the catalog of Greene & Ho (2007, red crosses), and the others were from the catalog of Shen et al. (2011, green circles). For the samples by Greene & Ho (2007), we plot the recomputed virial mass using the parameters of mass estimator in Shen et al. (2011). A total of 3749 objects among the samples from Shen et al. (2011) had been identified by the uniform criteria of SDSS quasars (Richards et al. 2002). We also present the results of the clustering analysis for these sub-samples. We divided our sample into four mass bins of log($M_{BH}/M_{\odot}$) = 6.5–7.2, 7.2–8.0, 8.0–9.0, and 9.0–10.0, and three redshift bins of $z = 0.1–0.3$, 0.3–0.6, and 0.6–1.0, to see mass and redshift dependencies. The number, the averaged
mass, and the averaged redshift of AGN samples for each mass range and redshift range are listed in Table 1.

For ~6% of AGNs in our sample, radio counterparts were found in the Faint Images of the Radio Sky at Twenty cm source catalog (Schneider et al. 2010). The percentage of objects with radio counterparts is higher for AGNs with higher BH mass. The fraction of AGNs with a radio counterpart is 14% at $M_{BH} > 10^9 M_\odot$. For ~12% of the sample AGNs, X-ray counterparts were found in the ROSAT catalog. The fraction of AGNs with X-ray detection is almost the same for all the BH mass ranges.

3. ANALYSIS METHOD

We have followed the method described in Shirasaki et al. (2011) for the cross-correlation analysis between AGNs and galaxies. The cross-correlation function of AGNs and galaxies $\xi(r)$ can be expressed as an excess in the number density of galaxies $\rho(r)$ relative to the average density $\rho_0$ at the AGN redshift

$$\xi(r) = \frac{\rho(r)}{\rho_0} - 1,$$

where $r$ represents the distance from an AGN.

In this analysis, the redshift of galaxies is not measured, thus a projected cross-correlation function $\omega(r_p)$ is calculated from projected number densities of galaxies $n(r_p)$:

$$\omega(r_p) = \frac{n(r_p) - n_{bg}}{\rho_0},$$

where $r_p$ represents the projected distance from an AGN at the redshift and $n_{bg}$ represents the surface density of background/foreground galaxies.

3.1. Estimating the Average Density and the Limiting Magnitude

Estimation of $\rho_0$ is crucial for this analysis. However, we cannot estimate $\rho_0$ directly from the data themselves since the information on the redshift is lacking. In this work, we estimated $\rho_0$ based on the luminosity function of galaxies obtained by previous studies (Cirasuolo et al. 2007; K band, $z \geq 0.5$; Gabasch et al. 2004; 150 nm, 280 nm, $u'$, and $g'$, $z \geq 0.6$; Gabasch et al. 2006; $r'$, $i'$, and $z'$, $z \geq 0.6$; Kochanek et al. 2001; $K$ band, $z = 0$; and Montero-Dorta & Prada 2009; $u'$, $g'$, $r'$, $i'$, and $z'$, $z = 0.1$). The solid lines represent fitting functions to parameterize $M_*$ and $\Phi(M_0)$ as a function of redshift. Top panel: $M_*$ for each rest-frame wavelength band. Bottom panel: number densities $\Phi(M_0)$ at a reference magnitude $M_0$. The reference magnitude $M_0$ for each wavelength band is $-18$ for 150 nm, 280 nm, and $u'$ band, $-20$ for $g'$ band, $-21$ for $r'$, $i'$, and $z'$ band, and $-22$ for $K$ band.

(A color version of this figure is available in the online journal.)

Figure 7. Parameters of the Schechter function derived by Cirasuolo et al. (2007; K band, $z \geq 0.5$; Gabasch et al. 2004; 150 nm, 280 nm, $u'$, and $g'$, $z \geq 0.6$; Gabasch et al. 2006; $r'$, $i'$, and $z'$, $z \geq 0.6$; Kochanek et al. 2001; $K$ band, $z = 0$; and Montero-Dorta & Prada 2009; $u'$, $g'$, $r'$, $i'$, and $z'$, $z = 0.1$). The solid lines represent fitting functions to parameterize $M_*$ and $\Phi(M_0)$ as a function of redshift. Top panel: $M_*$ for each rest-frame wavelength band. Bottom panel: number densities $\Phi(M_0)$ at a reference magnitude $M_0$. The reference magnitude $M_0$ for each wavelength band is $-18$ for 150 nm, 280 nm, and $u'$ band, $-20$ for $g'$ band, $-21$ for $r'$, $i'$, and $z'$ band, and $-22$ for $K$ band.

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and Montero-Dorta & Prada (2009) are plotted as a function of redshift for each rest-frame wavelength. $M_0$ is a reference magnitude where the luminosity function is normalized and parameterized as a function of redshift, and it is selected at a dimmer side of the $M_*$ magnitude. Those data points are fitted with a third-degree polynomial function of redshift as shown in Figure 7 as solid lines. The standard deviations of $M_*$ and $\phi(M_0)$ from the fitted functions are 0.2 mag and 15%, respectively. For the parameter $\alpha$, we used fixed values such as $-1.1$ for $\lambda < 400$ nm, $-1.25$ for $400 \leq \lambda < 1000$ nm, and $-1.0$ for $\lambda \geq 1000$ nm.

As $M_*$ and $\phi(M_0)$ at an arbitrary redshift for the eight wavelength bands can be calculated using the parameterization derived above, these parameters at an arbitrary wavelength are derived by interpolating them as a function of wavelength with a cubic spline method. In this way, we parameterized the luminosity function as a function of redshift and rest-frame wavelength. We estimate $\rho_0$ by means of the Schechter function with the parameters at the AGN redshift and wavelength corresponding to the observed $K$ band.

$\rho_0$ can be calculated by integrating $\phi(M; z, \lambda)$ to the absolute magnitude $M$ at an AGN redshift corresponding to an apparent limiting magnitude $m_{\text{limit}}$,

$$\rho_0 = \int_{m_{\text{low}}-DM(z)}^{m_{\text{limit}}-DM(z)} \phi(M; z, \lambda) dM,$$

where $DM$ is the distance modulus and $m_{\text{low}}$ is a lower boundary of the apparent magnitude.

As the limiting magnitude varies among the AGN samples, it was estimated from the measured magnitude distribution $N(m)$ as explained below. The observed magnitude distribution $N_{\text{obs}}(m)$ can be expressed as a multiplication of the true magnitude distribution $N_{\text{true}}(m)$ and the detection efficiency $\text{DE}(m)$:

$$N_{\text{obs}}(m) = N_{\text{true}}(m) \times \text{DE}(m).$$

We model $N_{\text{true}}(m)$ and $\text{DE}(m)$ as introduced in Shirasaki et al. (2011):

$$N_{\text{true}}(m) = \begin{cases} c \cdot 10^{(m-m_b)/\sigma_m} & (m < m_b) \\ c \cdot 10^{(m-m_b)/\sigma_m} & (m \geq m_b), \end{cases}$$

$$\text{DE}(m) = \left\{ \begin{array}{ll} 1 & (m < m_{\text{th}}) \\ \exp\left(-\frac{(m-m_{\text{th}})^2}{\sigma_m^2}\right) & (m \geq m_{\text{th}}). \end{array} \right.$$  

By fitting the model function of $N_{\text{obs}}(m)$ to the observed magnitude distribution, we obtained the model parameters $a$, $b$, $c$, $m_b$, $m_{\text{th}}$, and $\sigma_m$ for each area around an AGN sample. We determine $\rho_0$ as

$$\rho_0 = \int_{m_{\text{low}}-DM}^{\infty} \phi(M; z, \lambda) \text{DE}(M+DM) dM.$$  

We derive $m_{\text{limit}}$ by equating the right-hand sides of Equations (4) and (8).

The uncertainty of $\rho_0$ determined as explained above is dominated with the uncertainties of the model parameters $b$ and uncertainties of parameterization of the luminosity function, and they are taken into account as a systematic error in estimating the cross-correlation length. We estimate the uncertainty of $b$ as 0.04, which comes from the standard deviation of $b$ calculated for each AGN sample. Considering the uncertainty of $b$, corresponding uncertainties of $m_{\text{th}}$ and $\sigma_m$ are estimated by comparing those fitting parameters obtained by fixing the $b$ parameter to $b_{\text{best}} \pm 0.04$, where $b_{\text{best}}$ is the best-fitting parameter for the AGN sample. The uncertainty of $\rho_0$ originated from the uncertainties of $m_{\text{th}}$ and $\sigma_m$ (i.e., $b$) are calculated with error propagation. The uncertainty $\sigma_{\rho_0,b}$ is plotted as a function of redshift in Figure 8.

To evaluate the uncertainty of $\rho_0$ due to the uncertainties of parameterization of the luminosity function, we assumed uncertainties of $M_*$ and $\phi(M_0)$ to be 0.2 mag and 15%, respectively, which are the standard deviation of data points in Figure 7 from the fitting functions.

$$\sigma_{\rho_0,M_*}$$ is the uncertainty of $\rho_0$ due to the uncertainty of $M_*$, and it is plotted in Figure 8. The uncertainty of $\rho_0$ due to the uncertainty of $\phi(M_0)$ is independent from redshift and is a constant value of $\sigma_{\rho_0,\phi(M_0)} = 0.15$. Then the total uncertainty of $\rho_0$ is calculated as

$$\sigma_{\rho_0}^2 = \sigma_{\rho_0,b}^2 + \sigma_{\rho_0,M_*}^2 + \sigma_{\rho_0,\phi(M_0)}^2.$$  

3.2. Cross-correlation

We assume the power-law form for the cross-correlation function,

$$\xi(r) = \left( \frac{r}{r_0} \right)^{-\gamma},$$

where $r_0$ is a correlation length and $\gamma$ is a power-law index and fixed to 1.8, which is a canonical value measured by many other works. Then the projected cross-correlation function can be expressed as

$$\omega(r_p) = 2 \int_0^\infty \xi(r_p, \pi)d\pi = 2 \int_{r_p}^\infty \frac{r\xi(r)}{r^2 - r_p^2}dr = r_p \frac{\Gamma(\frac{\gamma}{2})}{\Gamma(\frac{\gamma+1}{2})} \frac{1}{\Gamma(\frac{3}{2})}.$$  

where $\pi$ and $r_p$ are distance along and perpendicular to the line of sight, respectively, and $\Gamma$ is the gamma function.
From Equations (2) and (11), the projected number density of galaxies around an AGN can be modeled as

\[ n(r_p) = C(\gamma) \times \rho_0 \times r_p \left( \frac{r_0}{r_p} \right)^\gamma + n_{bg}, \]  

(12)

where the term of the gamma function is represented by \( C(\gamma) \). By fitting this model function to the observed projected number density, we can derive the model parameters \( r_0 \) and \( n_{bg} \). \( \rho_0 \) is determined by the method described in Section 3.1. Since the clustering signature for each AGN is too weak to derive the parameters individually, we applied this fitting to the averages of \( n(r_p) \) and \( \rho_0 \) for a given AGN group.

\[ \langle n(r_p) \rangle = C(\gamma) \times \langle \rho_0 \rangle \times r_p \left( \frac{r_0}{r_p} \right)^\gamma + \langle n_{bg} \rangle, \]  

(13)

and derive \( r_0 \) and \( \langle n_{bg} \rangle \). The uncertainty of \( r_0 \) is calculated as the square root of the square sum of the systematic error derived from the uncertainty of \( \rho_0 \) described in Equation (9) and statistical error of 1\( \sigma \) by fitting \( \langle n(r_p) \rangle \). It should be noted that the cross-correlation function obtained by this method is not an average for the AGN group, but an average weighted with \( \rho_0 \). Thus, the result is biased to the low-\( z \) and high-sensitivity samples.

4. RESULTS

By the analysis described above, we have estimated the scale length of the AGN–galaxy cross-correlation for the whole sample to be \( r_0 = 5.8^{+0.8}_{-0.6} \) h\(^{-1}\) Mpc. This is comparable with or slightly smaller than the results of the previous studies of AGN–galaxy cross-correlation \( r_0 = 5.95 \pm 0.90 \) h\(^{-1}\) Mpc for X-ray AGNs at \( z = 0.7–1.4 \), Coil et al. 2009; 6.98 \pm 0.6 h\(^{-1}\) Mpc for optical AGNs at \( z < 1 \), Mountrichas et al. 2009; 6.0 \pm 0.5 h\(^{-1}\) Mpc for optical AGNs at \( 0.2 < z < 0.6 \), Padmanabhan et al. 2009). Donoso et al. (2010) found \( r_0 = 8.35 \pm 0.09 \) h\(^{-1}\) Mpc for radio AGNs and \( r_0 = 5.02 \pm 0.24 \) h\(^{-1}\) Mpc for optical AGNs at \( z = 0.4–0.8 \). Krumpe et al. (2012) derived that \( r_0 = 6.91^{+0.17}_{-0.18} \) h\(^{-1}\) Mpc at \( z = 0.16–0.36 \) between SDSS AGNs and the SDSS main-galaxy sample and \( r_0 = 7.21^{+0.21}_{-0.22} \) h\(^{-1}\) Mpc at \( z = 0.36–0.5 \) for SDSS AGNs and luminous red galaxies. Mountrichas et al. (2013) derived that \( r_0 = 4.4^{+0.1}_{-0.2} \) h\(^{-1}\) Mpc for X-ray selected AGNs at \( z \sim 0.1 \).

Now, we present the results of the cross-correlation analysis adopted for the four mass ranges described in Figure 6 and Table 1, to see the dependence of the clustering amplitude on BH mass. Figures 9 and 10 show the measured projected number density \( n(r_p) \) and projected cross-correlation function \( \rho(r_p) \), respectively, for each mass range. Four panels represent results for the mass ranges of \( \log(M_{\text{BH}}/M_\odot) = 9.0–10.0 \) (top left), \( 8.2–9.0 \) (top right), \( 7.5–8.2 \) (bottom left), and \( 6.5–7.5 \) (bottom right). The projected number density of the areas of circular rings plotted with the Poisson error bars. The solid lines denote least-\( \chi^2 \) fit by the power law (Equation (13)). The fitting parameters are summarized in Table 1.

Figure 11 shows the scale length \( r_0 \) of the cross-correlation as a function of the virial mass of SMBHs. Error bars of \( r_0 \)
Figure 10. Projected cross-correlation function of UKIDSS sources against projected distance from an AGN. The four panels show results for AGN samples in the four different mass ranges. The error bars show the uncertainty due to statistical error of projected number density. The solid lines denote least-$\chi^2$ fit by the power function (Equation (11)).

Figure 11. Scale length, $r_0$, of the cross-correlation between AGNs and galaxies as a function of virial mass of SMBHs. The error bars of $r_0$ denote square root of sum of the systematic error derived from the uncertainty of the estimation of $\rho_0$ and statistical error of 1$\sigma$. The vertical dotted lines show boundaries of mass ranges.

(A color version of this figure is available in the online journal.)

denote the square root of the square sum of the systematic error calculated from $\sigma_{\rho_0}$ described in Section 3.1 and the statistical error of 1$\sigma$. We can see a trend that $r_0$ increases as mass increases for $M_{BH} > 10^8 M_\odot$. When we consider only the statistical error, the significance of difference of $r_0$ is 9.6$\sigma$ between $\log(M_{BH}/M_\odot) = 7.5$–8.2 bin and 8.2–9.0 bin, and 3.4$\sigma$ between 8.2–9.0 bin and 9.0–10.0 bin. For $M_{BH} \lesssim 10^8 M_\odot$, we cannot see the significant mass dependence. These trends are also seen for the data set grouped with finer mass ranges.

Figure 12 shows $r_0$ for AGN samples from the catalog of Shen et al. (2011, green circles), which are identified by the uniform criteria of SDSS (Richards et al. 2002) and for samples of Greene & Ho (2007, blue triangles). As seen in the figure, the mass dependencies of both sub-samples are quite similar. We can see, however, a little offset between the results for the two sub-samples. This can be due to the systematic difference of the BH mass estimate with $\sim 0.2$ dex between the two catalogs as mentioned in Section 2.

We rejected sample AGNs with anomalous galaxy distribution around the AGNs, as described in Section 2 to remove the effect from foreground objects. To see whether we are removing real clustering by this rejection, we present the results of the analysis done both with and without the selection, in Figure 13. The blue triangles show the results without any sample rejection. We cannot find a significant clustering signal at $\log(M_{BH}/M_\odot) < 7.5$ for this analysis. The red squares are the fiducial results with the selection criteria described in Shirasaki et al. (2011). For the green circles, we also reject AGN samples with an extremely high or low projected number density ($n_{7 Mpc}^7$) of galaxies around them.

The analysis without selection gives slightly smaller $r_0$. This indicates that the clustering feature is weakened by foreground
of galaxies analysis with the contamination for the analysis without sample rejection. The green circles show the results for AGNs which are selected by uniform criteria of SDSS (Richards et al. 2002) among the samples from the catalog of Shen et al. (2011). The blue triangles show the results for the AGN samples extracted from the catalog of Greene & Ho (2007).

Figure 12. Comparison between source catalogs. The red squares are the results for the total sample (the same with Figure 11). The green circles show the results for AGNs which are selected by uniform criteria of SDSS (Richards et al. 2002) among the samples from the catalog of Shen et al. (2011). The blue triangles show the results for the AGN samples extracted from the catalog of Greene & Ho (2007).

(A color version of this figure is available in the online journal.)

Figure 13. Scale length $r_0$ of cross-correlation for different selection criteria for AGN samples. Blue triangles: results of the analysis without any sample rejection. Red squares: AGN samples with extremely inhomogeneous galaxy distribution around them are rejected by the criteria described in Shirasaki et al. (2011) in order to reduce the effect of foreground clusters which are accidentally located near the sample AGNs on the sky. The same with Figure 11. Green circles: samples with extremely high or low ($>1.5\sigma$) projected number density of galaxies $n_{7\text{Mpc}}$ are rejected. See also Section 2. Slightly larger $r_0$ is estimated for the analysis with the additional selection. On the other hand, the entire analysis gives almost the same relative mass dependence.

(A color version of this figure is available in the online journal.)

correlation length ($r_0$) against redshift for the samples of four BH mass ranges: $\log(M_{\text{BH}}/M_\odot) = 9.0-10.0$ (red squares), $8.2-9.0$ (green circles), $7.5-8.2$ (blue triangles), and $6.5-7.5$ (magenta inverted triangles). The results of mass and redshift range with $n_{\text{AGN}} < 200$ are not plotted because of very large uncertainty. The vertical dotted lines show boundaries of redshift ranges. Bottom panel: $r_0$ against BH mass for the samples of three redshift ranges: $z = 0.1-0.3$ (red squares), $z = 0.3-0.6$ (green circles), and $z = 0.6-1.0$ (blue triangles).

(A color version of this figure is available in the online journal.)

As seen in Figure 6, distribution of the BH mass in our sample depends on the redshift. This is because SMBHs with larger mass tend to be luminous and can be observed even at higher redshift. To see the dependence on the redshift, we divided the samples into three groups with redshift ranges of $z = 0.1-0.3$, $z = 0.3-0.6$, and $z = 0.6-1.0$. Figure 14 shows the estimated $r_0$ for the three redshift ranges and four mass ranges. As seen in the top panel of this figure, $r_0$ is not dependent on the redshift. Therefore, the increasing trend of $r_0$ seen in Figure 11 would not be due to the redshift bias. We could also see the mass dependence for the sub-samples of low redshift ($z = 0.1-0.3$, red squares) and intermediate redshift ($z = 0.3-0.6$, green circles). For the higher redshift sample ($z = 0.6-1.0$), the estimated error is too large to see the dependence on BH mass. We summarize the estimated $r_0$, $\langle \rho_0 \rangle$, and $\langle n_{bg} \rangle$ for each mass range and redshift range in Table 1.

To remove the possible redshift bias, we also present the mass dependence for sub-samples with the normalized redshift distributions. We constructed sub-samples as follows. For redshift bins with $\Delta z = 0.1$, the selection probability is determined to give the same redshift distribution for the four mass ranges. We randomly selected AGN samples following the selection probability and constructed a set of sub-samples. Figure 15 shows one example of the sub-sample. We constructed 10 sets of sub-samples and measured $r_0$ for them. For these sub-samples, there is no correlation between redshift and BH mass.

Figure 16 shows the mass dependence of $r_0$ for the re-sampled AGNs with normalized redshift distribution. We plot

4.1. AGN Redshift

As seen in Figure 6, distribution of the BH mass in our sample depends on the redshift. This is because SMBHs with larger mass tend to be luminous and can be observed even at higher redshift. To see the dependence on the redshift, we divided the samples into three groups with redshift ranges of $z = 0.1-0.3$, $z = 0.3-0.6$, and $z = 0.6-1.0$. Figure 14 shows the estimated $r_0$ for the three redshift ranges and four mass ranges. As seen in the top panel of this figure, $r_0$ is not dependent on the redshift. Therefore, the increasing trend of $r_0$ seen in Figure 11 would not be due to the redshift bias. We could also see the mass dependence for the sub-samples of low redshift ($z = 0.1-0.3$, red squares) and intermediate redshift ($z = 0.3-0.6$, green circles). For the higher redshift sample ($z = 0.6-1.0$), the estimated error is too large to see the dependence on BH mass. We summarize the estimated $r_0$, $\langle \rho_0 \rangle$, and $\langle n_{bg} \rangle$ for each mass range and redshift range in Table 1.

To remove the possible redshift bias, we also present the mass dependence for sub-samples with the normalized redshift distributions. We constructed sub-samples as follows. For redshift bins with $\Delta z = 0.1$, the selection probability is determined to give the same redshift distribution for the four mass ranges. We randomly selected AGN samples following the selection probability and constructed a set of sub-samples. Figure 15 shows one example of the sub-sample. We constructed 10 sets of sub-samples and measured $r_0$ for them. For these sub-samples, there is no correlation between redshift and BH mass.

Figure 16 shows the mass dependence of $r_0$ for the re-sampled AGNs with normalized redshift distribution. We plot
We divided our sample into three luminosity ranges of $L_{5100} < 10^{44.5}$ erg s$^{-1}$, $10^{44.5}$ erg s$^{-1} \leq L_{5100} < 10^{44.8}$ erg s$^{-1}$, and $10^{44.8}$ erg s$^{-1} \leq L_{5100}$ to see luminosity dependence, where $L_{5100}$ is the monochromatic continuum luminosity at rest-frame 5100 Å. The top panel of Figure 17 shows the dependence of $r_0$ on luminosity. We cannot find significant luminosity dependence for all four mass ranges. On the other hand, we could see the mass dependence at $M_{BH} > 10^8 M_\odot$ for all three luminosity ranges, as seen in the bottom panel. Therefore, we can conclude that the BH mass dependence seen in Figure 11 is not due to the dependence on luminosity.

Shen et al. (2009) argued that the amplitude of AGN–AGN auto-correlation depends weakly on optical luminosity. Donoso et al. (2010) found that the clustering amplitude varies with radio luminosity on scales less than ~1 Mpc but is almost independent of luminosity for the larger scale.

These results indicate that the clustering amplitude on a large scale depends on the mass of SMBHs but weakly depends on luminosity.

### 4.3. Completeness and Luminosity of the Galaxy Sample

As described in Section 3.1, we correct the incompleteness of the faint end of the galaxy sample by estimating the detection efficiency DE$(m)$ based on the magnitude distribution of the UKIDSS sample for each area around an AGN. There may...
be a criticism that the correction of the incompleteness of the galaxy sample is somehow biased to the luminosity of the galaxy sample. Figure 18 shows the cross-correlation length calculated for a complete galaxy sample that consists of bright galaxies with \( m < m_{\text{th}} \), where \( m_{\text{th}} \) is a threshold magnitude, below which \( \mathrm{DE}(m) = 1 \) (see Equation (7)). For this analysis, \( r_0 \) is also recomputed by integrating the luminosity function up to \( m_{\text{th}} \). This result also shows that the cross-correlation increases above \( M_{\text{BH}} \sim 10^7 M_\odot \). Therefore, the increasing trend is not due to the ambiguity that comes from using an incomplete galaxy sample.

It is known that brighter galaxies tend to cluster more strongly than dimmer galaxies. Thus, it might be possible to explain the larger cross-correlation length for more massive SMBHs by the bias due to the galaxy brightness. Figure 19 shows the cross-correlation length calculated for luminosity-limited samples. We selected the luminosity-limited galaxy samples which are defined as \( M \equiv m - \mathrm{DM}(z_{\text{AGN}}) - 22 \) and \( M < -23.5 \) for each AGN, where \( \mathrm{DM}(z_{\text{AGN}}) \) represents distance modulus for the AGN redshift. \( M \) is not the absolute magnitude for foreground and background galaxies, but they should make no contribution to the clustering signal and not affect \( r_0 \). For these analyses, we selected AGN samples with \( M_{\text{th}} \equiv m_{\text{th}} - \mathrm{DM} > -22.0 \) and \( M_{\text{th}} > -23.5 \), respectively (see also Figure 3). Therefore, these absolute-magnitude-limited galaxy samples are also “complete” (\( m < m_{\text{th}} \)). Although the error bar is relatively large, we can see the similar trend of the cross-correlation length against virial mass of SMBHs as Figure 11. The significance of the difference of \( r_0 \) by considering statistical error is 1.9\( \sigma \) for mass ranges between \( \log(M_{\text{BH}}/M_\odot) = 7.5–8.2 \) and \( 8.2–9.0 \), and 1.7\( \sigma \) for between \( 8.2–9.0 \) and \( 9.0–10.0 \), for the analysis with the \( M < -23.5 \) sample, and 3.8\( \sigma \) for between \( \log(M_{\text{BH}}/M_\odot) = 7.5–8.2 \) and \( 8.2–9.0 \) for the \( M < -22.0 \) sample. Therefore, we can conclude that the increase of the cross-correlation length seen in Figure 11 is not only due to the bias related with the galaxy brightness. The estimated scale length is larger than Figure 11 since brighter galaxies are more strongly clustered.

5. DISCUSSION

In the previous studies, Shen et al. (2009) have shown that most massive SMBHs are more strongly clustered than the remainders from auto-correlation analysis of quasars. It has also been shown that radio selected AGNs are more strongly clustered than the cases for the optically selected AGNs (Hickox et al. 2009; Donoso et al. 2010), and the characteristic BH mass of radio AGNs is higher than optically selected ones. For 2300 quasars at \( z = 0.6–1.2 \), Zhang et al. (2013) found that the clustering amplitude is larger for quasars with more massive BHs at a significance of \( \sim 1\sigma \), using photometric data from SDSS Stripe 82. Our results are consistent with these previous studies. These may indicate that the environments of galaxies have played an important role for the growth of high-mass SMBHs. The clustering amplitude is relevant to the mass of the host dark-matter halo and the frequency of major merger. If the mass growth of SMBHs is mainly driven by the major mergers of galaxies, massive SMBHs are expected to be in massive halos.

In contrast, we did not find a significant luminosity dependence. Luminosity is thought to represent gas accretion activity at this time. The activity of SMBHs is thought to be a transient event and not strongly correlate with large-scale structure. On the other hand, BH mass is thought to represent cumulative accretion history and merger history of BHs, and can be related with large-scale environment.

For less massive BHs with \( M_{\text{BH}} \lesssim 10^8 M_\odot \), the significant correlation between \( r_0 \) and \( M_{\text{BH}} \) is not seen in our study. BH mass has been thought to be correlated with the mass of dark-matter halos (e.g., Ferrarese 2002). However, Kormendy & Bender (2011) found that the mass of SMBHs does not directly correlate with dark-matter halo mass, at least for low-mass SMBHs in disk galaxies, based on the observations of nearby SMBHs for which the mass of the host dark halos is derived by the stellar kinematics. Graham (2012) and Scott et al. (2013) examined the relation between \( M_{\text{BH}} \) and mass of the host spheroid, \( M_{\text{sph}} \), and found that the slope of the \( \log M_{\text{BH}} - \log M_{\text{sph}} \) relation changes at \( M_{\text{BH}} = 2 \times 10^8 M_\odot \).

One possible scenario to explain the absence of the positive mass dependence for \( M_{\text{BH}} \lesssim 10^8 M_\odot \) would be that the less massive BHs could be formed in the isolated galaxies by secular processes. If they have grown by secular processes, then the mass of a seed BH should be much larger than a typical stellar mass BH (for a review, see, e.g., Volonteri 2010). Some authors (Lodato & Natarajan 2006; Begelman et al. 2006) argue that
SMBHs with $10^4 - 10^6 M_\odot$ are formed through the direct collapse of pre-galactic gas at $z > 10$. Such a heavy seed BH can grow to $\sim 10^7 - 10^8 M_\odot$ by a few Gyr without a BH merger under the assumption that the mass accretion rate is $\sim 0.1$ times the Eddington rate. Another scenario would be that they are in a growing phase by the major mergers of galaxies.

For the clustering amplitude of less massive SMBHs, the contribution of the AGNs hosted in satellite galaxies in the growing phase by the major mergers of galaxies.

Eddington rate. Another scenario would be that they are in a large area of the sky. The estimated correlation length ranges of cosmic variance owing to the large sample covering the LAS by means of VO tools. Our results are free from the effect of an SMBH.

Further investigation of less massive BHs is crucial to understand the formation and evolution mechanisms of an SMBH.

6. CONCLUSIONS

We have investigated the clustering of galaxies around 9394 AGNs for $z = 0.1 - 1$. We obtained the galaxy data of UKIDSS LAS by means of VO tools. Our results are free from the effect of cosmic variance owing to the large sample covering the large area of the sky. The estimated correlation length ranges between 4 and $10 h^{-1}$ Mpc depending on BH mass, and depends neither on redshift for $z = 0.1 - 1$ nor on luminosity. The results may indicate that higher mass BHs reside in a more clustered environment for $M_{BH} > 10^8 M_\odot$.

While our results show a positive mass dependence for $M_{BH} > 10^8 M_\odot$, our results for $M_{BH} \lesssim 10^8 M_\odot$ show no significant mass dependence. Although our sample of less massive BHs is small, this would give a critical mass scale for the emergence of an environment effect for BH growth.

In this study, the redshift range where the BH mass dependence of the cross-correlation is measured with good accuracy is limited to below $z \sim 0.6$. This is because the number density of UKIDSS LAS galaxies is too low at higher redshift, and also the systematic error due to the uncertainty of the $M_*$ parameter of the luminosity function is too large. To understand the relation of the BH mass accretion history and its environment, it is crucial to observe its evolution up to at least redshift two where the number density of QSOs is maximal and the mass accretion is expected to be the most prosperous. To reduce the uncertainty, it is crucial to perform deeper observations so that the limiting magnitude reaches well beyond the characteristic luminosity of galaxies at AGN redshifts. At redshifts larger than 0.5, the dominant factor to the uncertainty of $\rho_0$ is an uncertainty of $M_*$ parameterization and the $\rho_0$ uncertainty becomes larger than 20%. Observations two magnitudes deeper will extend the redshift range where the uncertainty of $\rho_0$ is less than 20% up to 1.0. Future instruments such as Hyper Suprime-Cam (HSC) can measure the AGN environment more accurately with good statistics. When the survey is performed with 26 mag in the $r$ band with HSC, we can estimate $\rho_0$ with accuracy less than 20% up to redshift 2, and as a result can estimate $r_0$ with an accuracy less than 10%. Such a deep and wide survey would reveal the mechanism of AGN evolution at an important epoch at which its activity was the most prosperous.

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