QUasar–GALAXY CLUSTERING THROUGH PROJECTED GALAXY COUNTS AT z = 0.6−1.2

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ABSTRACT

We investigate the spatial clustering of galaxies around quasars at z = 0.6–1.2 using photometric data from Sloan Digital Sky Survey Stripe 82. The quasar and galaxy cross-correlation functions are measured through the projected galaxy number density n(rp) on scales of 0.05 < r_p < 20 h^{-1} Mpc around quasars for a sample of 2300 quasars from Schneider et al. We detect strong clustering signals at all redshifts and find that the clustering amplitude increases significantly with redshift. We examine the dependence of quasar–galaxy clustering on quasar and galaxy properties and find that the clustering amplitude is significantly larger for quasars with more massive black holes or with bluer colors, while there is no dependence on quasar luminosity. We also show that quasars have a stronger correlation amplitude with blue galaxies than with red galaxies. We finally discuss the implications of our findings.

Key words: galaxies: clusters: general – large-scale structure of universe – quasars: general

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1. INTRODUCTION

Evidence has been mounting in the local universe that most massive galaxies host supermassive black holes at their centers (Kormendy & Richstone 1995; Gebhardt et al. 2000; Merritt & Ferrarese 2001). These black holes are the relics of past nuclear activity, i.e., growth via accretion of gas in the galaxy (e.g., Soltan 1982; Small & Blandford 1992; Yu & Tremaine 2002). The strong link between black holes and their host galaxies, as revealed by correlations between black hole mass and the stellar velocity dispersion or the mass of the host galaxy bulge in local galaxies (M_{BH}–σ, M_{BH}–M_\text{bul} relation; e.g., Magorrian et al. 1998; Gebhardt et al. 2000; Ferrarese & Merritt 2000; Merritt & Ferrarese 2001; Ueda et al. 2003), implies the co-evolution of black holes with their host galaxies. This is further sustained by the similar redshift evolution of the overall star formation rate and the quasar luminosity function. However, it remains unclear what drives this co-evolution. Important issues continue to be poorly understood, such as what triggers the gas fueling and how nuclear activity affects the subsequent evolution of host galaxies. The answers to these questions lie in the various correlations between active black holes and their host galaxies as well as the environment of their hosts. However, it is difficult to directly study the host galaxy of a quasar, even at quite moderate redshifts, because a quasar outshines its host by a large factor.

Quasar clustering and quasar–galaxy cross-correlation provide a very effective way to quantify both environmental effects and host properties in a statistical sense. The current cosmological models show that structures (dominated by dark matter) in the universe grow from small primordial density fluctuations, detected in the cosmic microwave background, in the early universe mainly via gravitational interaction. Galaxies populate the collapsed dark matter halos (DMHs), and their properties are expected to be closely related to the mass of the DMHs (e.g., Scoccimarro et al. 2001; Berlind & Weinberg 2002; Yang et al. 2003; Kravtsov et al. 2004; Zheng et al. 2005). In other words, galaxies trace DMHs. By measuring the clustering properties of quasars and galaxies, one can deduce which DMH may host a quasar. The cross-correlation of quasars and normal galaxies can tell us how quasars and galaxies are physically related (e.g., Hopkins et al. 2007). These relations can also be used to constrain the duty cycles of nuclear activity (e.g., Shankar et al. 2010).

There are two different approaches to measuring such clustering. The first one is counting the excess surface number density of galaxies at various distances from quasars. This overdensity has a simple relation to the angular cross-correlation function (CCF) between quasars and galaxies. The angular correlation function is widely used in the characterization of the large scale structure of the universe. This method works even in the absence of redshift information on galaxies. On the other hand, if the redshifts of galaxies are known, there is a more precise way to describe the clustering properties using the two-point correlation function in three dimensional space.

At low redshifts, the cross-correlation between active galactic nuclei (AGNs) and galaxies is well studied. Based on analysis of the angular CCF between AGNs and galaxies or the overdensity of galaxies around AGNs, earlier works indicated that quasars and Seyfert galaxies are located in rich clusters of galaxies (e.g., Bahcall 1969; Yee & Green 1984, 1987; Ellingson et al. 1991; Hill & Lilly 1991; Laurikainen & Salo 1995; De Robertis et al. 1998; Smith et al. 1995, 2000). However, recent studies of large, low redshift AGN samples from the Sloan Digital Sky Survey (SDSS) or 2 Degree Field (2dF) survey suggested that AGNs do not reside in a significantly different environment or that they even systematically avoid high galaxy-density regions compared with a matched control sample of galaxies (Croom et al. 2004; Sorrentino et al. 2006; Coldwell & Lambas 2006; Li et al. 2007). It appears that the difference is partly attributed to the luminosity or black hole mass dependence of clustering properties and partly to the corrections of various selection effects (e.g., Croom et al. 2005; Fine et al. 2006; Myers et al. 2006; da Ángela et al. 2008; Coil et al. 2009; Hickox et al. 2009). Serber et al. (2006) studied the environments of quasars (z ≲ 0.4, M_r ≲ −22) and reported that quasars reside in higher locally overdense regions and that the local density excess increases with decreasing scale at distances less than 0.5 Mpc from quasars. They also found that there is a luminosity dependence on the density enhancement.
Strand et al. (2008) explored the relationship between AGN environment and the type, luminosity, and redshift of the AGN itself, and reached a similar conclusion that higher luminosity ($M_i \leq -23.2$, $M_i = -23.87$) AGNs have more overdense environments compared to lower luminosity ($M_i > -23.2$, $M_i = -22.75$) AGNs. They also presented marginal evidence for a redshift evolution of type I quasar environments and no difference between the environments of type I and type II quasars. These studies are consistent with the popular scenario about the formation of AGNs from simulations: quasars are triggered through gas-rich mergers while low luminosity AGNs derive from secular evolution, which depends much more weakly on environment (e.g., Hopkins & Hernquist 2009; Lutz et al. 2010; Mullaney et al. 2010).

At higher redshifts, a consensus has yet to be reached on whether quasar clustering depends on redshift or quasar properties. Barr et al. (2003) indicated that there is no evidence for an environmental redshift dependence based on observations of 21 radio-loud quasars at $0.6 < z < 1.1$. Adelberger & Steidel (2005) reported a similar result for quasars at $1.5 < z < 3.5$. Shen et al. (2009) did not see a significant difference in clustering strength when dividing the quasar sample by luminosity, black hole mass, or color at $z \sim 1.4$. Coil et al. (2007, hereafter C07) found that the cross-correlation amplitude of quasars and galaxies is similar to the auto-correlation function (ACF) of DEEP2 galaxies; no significant dependence was found with either luminosity or redshift. However, Croom et al. (2002, 2005) showed that the redshift-space two-point correlation amplitude has a weak dependence on quasar luminosity, but increases with redshift in the range of $0.5 < z < 2.5$. By combing the 2dF quasar redshift survey (2QZ) with the fainter 2dF-SDSS LRG and QSO (2SLAQ) survey, da Angela et al. (2008) found a stronger redshift dependence, and confirmed the independence of luminosity at a fixed redshift. Shirasaki et al. (2011) found that AGNs at higher redshifts reside in denser environments than those at lower redshifts, and faint and bright AGNs displayed similar correlation amplitudes at $0.3 < z < 1.8$ based on measurements of the overdensity of galaxies around quasars using photometric data derived from deep Subaru Suprime-Cam images.

Unlike the optically selected type 1 AGNs in the above studies, the X-ray-selected AGN sample, especially those with Chandra and XMM data, is not strongly biased against obscured AGNs. Also, X-ray observations provide the deepest AGN surveys. The clustering analysis based on the spectroscopic galaxy samples and the X-ray-selected AGN samples from the ROSAT All-Sky Survey (e.g., Krume et al. 2010) and Chandra and XMM data (e.g., Gilli et al. 2005, 2009; Yang et al. 2006; Coil et al. 2009) can reveal the clustering properties of distant low luminosity AGNs or AGNs missed by color-based optical surveys. Coil et al. (2009) found that the X-ray-selected AGNs in red host galaxies are significantly more clustered than those in blue host galaxies, but no dependence of the clustering on optical or X-ray luminosity or hardness ratio was found. However, Krume et al. (2010) detected a significant dependence of the X-ray luminosity on the clustering amplitude (see also Koutoulidis et al. 2013). The clustering amplitude for low $L_X$ AGNs is similar to that of blue star-forming galaxies, while the clustering amplitude for the high $L_X$ sample is consistent with the clustering of red galaxies.

These controversial results may be caused by the selection effects of galaxy and AGN samples. In most experiments, the galaxy samples are derived either spectroscopically or photometrically. In a spectroscopic sample, the redshifts of galaxies can be precisely measured, but only bright galaxies are targeted. Moreover, the spectroscopic targets are usually selected via optical colors that may introduce selection bias against certain type of galaxies. For the multi-wavelength photometric sample, the galaxy samples are selected with certain color cuts and the galaxy redshifts are estimated through photometric redshift methods that are less accurate and subject to some outliers. Thus, an unbiased galaxy sample is the most important part of an investigation of AGN environments.

In this paper, we present measurements of the quasar–galaxy cross-correlation through the projected galaxy number counts around quasars, using all photometric data from SDSS Stripe 82 at $0.6 < z < 1.2$. In this work, we do not use any color cuts to select our galaxy sample. The quasar and galaxy samples used in this paper are described in Section 2. The method for calculating overdensities, the galaxy luminosity function in the observers’ frame, and the estimate of cosmic variance are described in Section 3. The results of clustering analysis are presented in Section 4. The implications of our findings are discussed in Section 5. Throughout this paper, we assume a Λ-dominated cosmology with $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.28$, and $\Omega_\Lambda = 0.72$. We define $h = H_0/(100$ km s$^{-1}$ Mpc$^{-1}$) and quote correlation lengths in co-moving $h^{-1}$ Mpc.

2. THE DATASETS AND DATA SELECTION

The SDSS imaged 11,663 deg$^2$ of the sky in five broad bands, $u, g, r, i, z$, with effective wavelengths of 3550, 4770, 6230, 7620 and 9130 Å, respectively (Fukugita et al. 1996; Gunn et al. 1998, 2006; Smith et al. 2002) and obtained spectra of over a million galaxies and quasars in over 8000 deg$^2$ of high Galactic latitude sky (York et al. 2000; Abazajian et al. 2009). The final photometric catalog provides accurate astrometry (Pier et al. 2003) and photometry for over 357 million unique objects (Lupton et al. 1999, 2001; Hogg et al. 2001; Smith et al. 2002; Stoughton et al. 2002; Ivezić et al. 2004; Tucker et al. 2006; Padmanabhan et al. 2008).

In the SDSS imaging survey, the Celestial Equator Stripe (Stripe 82) has repeated photometry in a rectangular region covering about 270 deg$^2$ ($\delta_{2000}$ from $-1.266$ to $+1.266$ deg and $\alpha_{2000}$ from $-59$ to $60$ deg; see panel (a) of Figure 1), including approximately 12 × 739 contiguous fields of size $9' \times 13'$ each. Stripe 82 has been imaged approximately 80 times (Figure 3 of Abazajian et al. 2009) and the photometry reaches $\sim 2$ mag deeper than any individual scan. Due to different observing conditions, the photometric depths of these fields in Stripe 82 are not uniform and almost go deeper as right ascension ($\alpha_{2000}$) increases.

From the co-added images of Stripe 82, we find that the photometric precision is highest in the $i$-band.\(^3\) To determine the survey depth of a field, we calculate the apparent magnitude distribution for all sources in the field. Since the number will drop quickly at magnitudes fainter than the survey depth, there is a well-defined peak in this distribution. We choose the magnitude that the distribution peaks at as the magnitude threshold ($i_{th}$) of the field under consideration. Assuming that the galaxy number $N(i)$ at an apparent magnitude $i$ follows log $N(i) \propto i$, we can extrapolate the number counts at a magnitude of $i < i_{th}$ to $i_{th}$ to obtain a reference number for each field. We calculate

\( ^3 \) The $i$-band means SDSS $i$-band in this paper, and the i-band magnitude we use is the “$i_{model}$” magnitude corrected for Galactic extinction using the extinction map of Schlegel et al. (1998) and the reddening curve of Fitzpatrick (1999).
Figure 1. Panel (a): distribution of photometric objects (gray dots) and quasars from Schneider et al. 2007 (red filled circles) at $0.6 < z < 1.2$ in the SDSS Stripe 82 field. Panels (b)–(d): plots of quasar luminosity ($M_i$), black hole mass ($M_{BH}$) and optical color ($\beta_{3K,4K}$) against redshift. The green curve in panel (d) shows the median $\beta_{3K,4K}$ as a function of redshift ($\bar{\beta}(z)$). The relative optical colors of blue quasars are $\beta_{3K,4K} - \bar{\beta}(z) < -0.22$ and $\beta_{3K,4K} - \bar{\beta}(z) > 0.24$ for red quasars. (A color version of this figure is available in the online journal.)

Figure 2. Distribution of $i_m$ for all the fields in Stripe 82. The value of $i_m$ has a large dispersion, ranging from 21.2 to 23.8. The dotted line and dashed line show the 10th and 90th percentiles of the distribution, respectively.

Our galaxy sample is selected from the SDSS DR7 Stripe 82 calibrated object catalog (SDSS run = 100006 (South strip) and 200006 (North strip) in the Data Archive Server, 106 and 206 in the Catalog Archive Server; Abazajian et al. 2009), but we do not use photometric redshift information. We do not remove stars from the sample either because they will not significantly affect our results. The reasons are as follows. First, Stripe 82 is a high Galactic latitude region, which is not a densely populated area for stars. The stars constitute about 7% of all photometric objects. Second, although there is a significant gradient in the stellar density in Stripe 82, its amplitude on the scales of interest is very small. Finally, there is no spatial correlation between quasars and stars so that the stars can be considered as background using our random quasar samples (see Section 3.1). This is verified in Section 4.1 (Figure 6 and 7), in which we demonstrate that the clustering signature is not present in the random fields.

We take our quasar sample from the SDSS DR5 quasar catalog (Schneider et al. 2007). In this catalog, spectroscopic targets are selected mostly according to their location in multidimensional SDSS color space, supplemented by X-ray- and radio-detected sources. Approximately half of the quasars have $i < 19$; nearly all have $i < 21$. These two values correspond to the $i$ magnitude limits for $z < 3$ and $z > 3$ candidates selected by optical colors, i.e., $ugri$ and $griz$ color cubes (Richards et al. 2002; Schneider et al. 2007). The final catalog contains 77,429 objects all of which have at least one emission line with a FWHM larger than 1000 km s$^{-1}$ or interesting/complex absorption features. Redshifts range from 0.08 to 5.41. The $K$-corrected $i$-band absolute magnitudes of these quasars are more luminous than $M_i = -22.0$. The catalog provides positions with accuracies better than 0.2′′ rms and five-band CCD-based photometry with a typical accuracy of 0.03 mag. There are 9244 quasars that fall in Stripe 82. According to the photometric magnitude limits and galaxy luminosity functions presented in Section 3.2, we set the redshift range as $0.6 < z < 1.2$ to ensure that a significant fraction of galaxies are detected in the SDSS Stripe 82. Applying this redshift cut, we obtain 2300 quasars in the final sample.

In panel (a) of Figure 1, we show the spatial distribution of these quasars (red filled circles). There is an under-dense zone at $\alpha_{2000} \approx -40$ deg. As mentioned above, the quasar candidates were mainly selected from the photometric objects.
by their colors. We find that there are scarcely any objects with $i > 19$ at $-45 < \alpha_{12000} < -35$ deg in the $\alpha_{12000} - i$ diagram for all DR5 quasars located in Stripe 82; the so-called high-redshift candidates are absent. The only quasars are dozens are selected from X-ray and radio objects. This does not affect our final results as we are not interested in the high redshift quasars.

3. THE CROSS-CORRELATION OF QUASARS AND GALAXIES

3.1. The Galaxy Density Profile around Quasars

The CCF between quasars and galaxies, $\xi(r)$, measures the excess probability of finding a galaxy in a volume at a distance $r = (r_p^2 + \pi^2)^{1/2}$ from a randomly chosen quasar, where $r_p$ and $\pi$ are coordinates perpendicular to and along the line of sight, respectively (Peebles 1980). To measure the correlation function from the spatial distribution of galaxies, one usually counts galaxy–quasar pairs over a two-dimensional grid of separations to estimate $\xi(r_p, \pi)$, and then integrate $\xi(r_p, \pi)$ along the $\pi$ direction up to a certain separation to eliminate redshift distortions in the $\pi$ direction (e.g., Peebles 1980). Because spectroscopic redshifts are not available for galaxies in the SDSS Stripe 82 region, we cannot use this conventional method. In this section, we will describe our projected number density method to measure the cross-correlation between quasars and galaxies.

In this method, all the photometric objects are projected on the celestial sphere. For a quasar with a known redshift $z$, we calculate the projected distance ($r_p$) between a photometric object and the quasar assuming that both objects are at the same redshift. The projected number density of galaxies ($n(r_p)$) as a function of the projected distance to the quasar ($r_p$) is then obtained. Naturally, $n(r_p)$ includes the contributions of foreground and background galaxies and stars, and the galaxies surrounding the quasar. The latter quantity has a close connection to the CCF.

By assuming a power-law form of the correlation function (e.g., Yee & Green 1987), the average number density ($\rho(r)$) of galaxies at a distance ($r$) from the quasar can be written as:

$$\rho(r) = \left(\frac{r_0}{r}\right)^{\gamma} \rho_0, \quad (1)$$

where $r_0$ is the cross-correlation amplitude, $\gamma$ is the power-law slope, and $\rho_0$ is the galaxy density at the redshift of the quasar. The first term in the bracket represents the cross-correlation. We rewrite $\rho(r)$ as a function of $r_p$ and $\pi$ (Davis & Peebles 1983):

$$\rho(r_p, \pi) = \left[1 + (\pi/r_p)^2\right]^{-\gamma/2} (r_0/r_p)^{\gamma} \rho_0 + \rho_0. \quad (2)$$

Then, we derive the projected galaxy number density $n(r_p)$:

$$n(r_p) = \int_{-\pi}^{\pi} d\pi \rho(r_p, \pi) + n_{bg},$$

$$= \rho_0 \left(\frac{r_0}{r_p}\right)^{\gamma} \int_{-\pi}^{\pi} d\pi \left[1 + \left(\frac{\pi}{r_p}\right)^2\right]^{-\gamma/2} + 2\pi \rho_0 + n_{bg},$$

$$= \rho_0 r_p \left(\frac{r_0}{r_p}\right)^{\gamma} \int_{-\pi}^{\pi} d\pi \left[1 + \left(\frac{\pi}{r_p}\right)^2\right]^{-\gamma/2} + n_{bg},$$

$$(if \quad \pi \gg r_p)$$

$$= \rho_0 r_p \left(\frac{r_0}{r_p}\right)^{\gamma} \frac{\Gamma[1/2] \Gamma[(\gamma - 1)/2]}{\Gamma[\gamma/2]} + n_{bg},$$

$$= \rho_0 \omega(r_p) + n_{bg}, \quad (3)$$

where $\Gamma$ is the gamma function. The total background density $n_{bg}$ is the sum of the density of foreground and background galaxies and stars ($n_{bg}$), and the average galaxy density (2$\pi$ $\rho_0$) at the quasar’s redshift. $\omega(r_p)$ is the projected CCF, which is obtained by integrating the two-point CCF $\xi(r) = \rho(r)/\rho_0 - 1 = (r_0/r)^{\gamma}$ along the line of sight (Peebles 1980). To derive the values of $\omega(r_p)$, we need to know $n(r_p)$, $n_{bg}$, and $\rho_0$ from observational data.

The projected and background surface densities, $n(r_p)$ and $n_{bg}$, can be estimated using photometric catalogs. Let us consider the surface density around the $j$th quasar first. In the case where all nearby galaxies around the quasar fall in the same field of depth $i_1$, the surface density $n_j(r_p)$ of galaxies brighter than $i_1$ is simply the number of galaxies in the annulus between a radius $r_p$ and $r_p + \Delta r_p$. When the annulus intersects with more than one field, we measure $n_j(r_p)$ using an “effective” area for each depth, as we illustrate in the following example.

As shown in Figure 3, the annulus intersects with four fields (labeled “A” to “D”) with photometric depths in the $i$-band of 20.24, 22.3, 23.6, and 23.8 mag, respectively. If we calculate $n_j(r_p)$ within the $i$-band magnitude range 21.0 < $i$ < 22.4, the four fields are all “effective” fields and then $n_j(r_p) = N_j(r_p)/S(r_p)$, where $S(r_p)$ is the area of intersection between the “effective” fields and an annulus with projected radii between $r_p$ and $r_p + \Delta r_p$. In other words, $S(r_p)$ is the sum of the green shaded areas in the four fields shown in Figure 3. If the $i$-band magnitude range of interest is 23.2 < $i$ < 23.6, then the “effective” fields are just the last two fields and $S(r_p)$ is the sum of the shaded areas in the last two fields (“C” and “D”). $N_j(r_p)$ is the total number of photometric objects in the area $S(r_p)$.

For a total of $m$ quasars, the projected number density for each magnitude bin is estimated as: $n(r_p) = \sum_{j=0}^{m} N_j(r_p)/\sum_{j=0}^{m} S_j(r_p)$. Here, $S_j(r_p)$ is the area of intersection between the “effective” fields ($i_b \geq i_1$) and an annulus with projected radii between $r_p$ and $r_p + \Delta r_p$ from the $j$th quasar and $N_j(r_p)$ is the number of galaxies in the intersection.

To estimate $n_{bg}$, we construct $N_{f, 20}$ mocked random samples by placing $m$ objects randomly in the Stripe 82 field. We assign redshifts to these fake objects so that the redshift distribution in each sample is the same as that of our quasar sample. According to Equation (3), the projected galaxy number density around objects is equal to $n_{bg}$, since they are not spatially correlated ($\omega(r_p) = 0$). We therefore apply the method shown above to determine $n_{bg}$ for each random quasar sample. Finally, $n_{bg}$ is the value averaged over the results for these $N_r = 20$ random position samples. We compute $\rho_0 = \sum_{j=0}^{m} N_j(r_p)/m$, where $\rho_{j, 0}$ is the number density of galaxies with $i$-band apparent magnitudes of $i_2 < i < i_1$ at redshifts similar to the $j$th quasar. In other words, $\rho_{j, 0}$ is the integration of the luminosity function of galaxies from $i = i_1$ to $i_2$. The error on $\rho_{j, 0}$ is propagated from the errors of the parameters of the Schechter luminosity function; we finally obtain the error on $\rho_0$ based on the errors on $\rho_{j, 0}$. The errors of the Schechter function parameters are correlated. As such, we will overestimate the error bar. The luminosity function will be constructed in the next subsection.

3.2. Estimation of $\rho_0$ from the Luminosity Function

As discussed in the last paragraph of Section 3.1, we need to know the number density of galaxies in an apparent magnitude range at the redshift of a quasar in question. In principle, one can derive this value by integrating the galaxy luminosity function at that redshift over a luminosity range, which is
Figure 3. Cartoon of the $n(r_p)$ measurement. Assume that the photometric depth in the $i$-band ($i_{\text{th}}$) of the four Stripe 82 fields ("A" to "D") is 22.4, 23.2, 23.6 and 23.8 mag, respectively. The black filled circle is the position of a quasar. If we calculate $n(r_p)$ within the $i$-band magnitude range $21.0 < i < 22.4$, the four fields are all "effective" fields. Then, $n(r_p) = N(r_p)/S(r_p)$, where $S(r_p)$ is the area of intersection between the "effective" fields and an annulus with projected radii between $r_p$ and $r_p + \Delta r_p$ and is the sum of the green shaded area in the four fields. However, if the $i$-band magnitude range we want to calculate is $23.2 < i < 23.6$, then the "effective" fields are just the last two fields, and $S(r_p)$ is the sum of the shaded area in the last two fields ("C" and "D"). $N(r_p)$ is total number of photometric objects in the region of $S(r_p)$.

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

transformed from the given range of apparent magnitude. Galaxy luminosity functions have been obtained by many authors for samples at $0.6 < z < 1.2$ (e.g., Gabasch et al. 2004, 2006; Ilbert et al. 2005, 2006; Zucca et al. 2006; Cirasuolo et al. 2007). These luminosity functions are all at a specific band in the rest frame of the galaxies, while we are interested in the luminosity functions in the observed waveband. Because we do not know the redshifts of our photometric galaxies, it is impossible to apply k-corrections. Therefore, we have to calculate new galaxy luminosity functions based on another deep field observation with galaxy redshifts available: a deep and homogeneous $i_{\text{Subaru}}$-band selected multi-waveband catalogue (Gabasch et al. 2008) from the Cosmic Evolution Survey (COSMOS), the largest survey imaging a 2 deg$^2$ equatorial field with sufficient depth (Scoville et al. 2007). It is the optimal sample for obtaining the galaxy luminosity functions that this work requires; cosmic variance will be discussed in the following subsection.

This catalog has a formal completeness limit of 50% for point sources of $i_{\text{Subaru}} \sim 26.7$ and comprises about 290,000 galaxies with observations in eight bands ($u_{\text{CFHT}}, B_{\text{Subaru}}, V_{\text{Subaru}}, r_{\text{Subaru}}, i_{\text{Subaru}}, z_{\text{KPGN}}, H_{\text{KPGN}},$ and $K_{s,\text{KPGN}}$); these bands are used to derive photometric redshifts. The accuracy of the photometric redshifts is $\Delta z/(z_{\text{spec}} + 1) \leq 0.035$ with only $\sim$2% outliers, based on comparisons with the spectroscopic redshifts of 162 galaxies in the redshift range $0 \leq z \leq 3$ (Bender et al. 2001; Gabasch et al. 2004). We use several galaxy spectral energy distribution (SED) templates from Coleman et al. (1980) and Kinney et al. (1996; see the left panel of Figure 4) to fit the eight bands observed for each object in this catalog. Then, we use the best fitting SED to derive SDSS $u$-,$r$-, and $i$-band magnitudes, which we are interested in.

The luminosity function of galaxies, $\phi(L)$, is defined as $dn(L) = \phi(L)dL$, where $dn(L)$ is the number density of galaxies with a luminosity in the interval $L \pm dL/2$. Generally, the number density is computed by dividing the number of galaxies in each magnitude bin by the volume $V_{\text{bin}}$ in a given redshift interval $[z_{\text{low}}, z_{\text{high}}]$. Since some faint galaxies are invisible in the whole survey volume, the $V/V_{\text{max}}$ correction must be performed (Schmidt 1968). Given the magnitude limit of the observations, we can obtain the maximum redshift $z_{\text{max}}$ for each object at which this object can be observed. Then, this object is weighted by $V_{\text{bin}}/V_{\text{max}}$, where $V_{\text{max}}$ is the volume enclosed between $[z_{\text{low}}, \min((z_{\text{high}}, z_{\text{max}}))]$. The resultant luminosity functions in three redshift ranges are shown in Figure 5.

The luminosity functions based on photometric redshifts from Subaru might be contaminated by spurious detections such as stars, AGNs, or blended objects in the very bright magnitude bins (see Gabasch et al. 2008). We exclude the very bright magnitude bins ($i$-band absolute magnitude $\leq -23.0$), then use the Schechter luminosity function (Schechter 1976) to fit the data. The fitting results are also shown in Figure 5 for comparison. We also derive the luminosity functions of two types of galaxies: red and blue (Figure 5); these luminosity functions will be used in the quasar and different type galaxy clustering measurements. Our test shows that the blue spectra (blue curves in the left panel of Figure 4) at the redshifts of interest ($0.6 < z < 1.2$) have $u - r < 0.8$ (observed frame), while the $u - r$ color of the red spectra (red curves in the left panel of Figure 4) are redder than 0.8. Details of the test are described below: (1) SED types of galaxies with $0.6 < z < 1.2$ in Gabasch’s COSMOS galaxy catalog are confirmed (the second paragraph of Section 3.2), (2) galaxies are divided into blue or red galaxy subsamples by their SED types, (3) photometric magnitudes in SDSS $u$- and $r$-bands are obtained from the convolution from the best-fitting SED. When we compared the $u - r$ color distributions of all COSMOS galaxies in the blue and red subsamples, a clear line at $u - r = 0.8$ can effectively divide blue/red galaxies in the diagram (the right panel of Figure 4). Thus, the dividing line is adopted as the criterion to distinguish blue and red galaxies as we calculate the
Figure 4. Left panel: SEDs (empirical templates from Coleman et al. 1980 and the “SB2” and “SB3” starburst spectrum from Kinney et al. 1996) grouped according to spectral type. Blue curves show the blue galaxy type and red curves show the red galaxy type. More details are given in the text. Right panel: color distribution of galaxies in the COSMOS field with blue SEDs (blue histogram) and red SEDs (red histogram). The vertical dashed line indicates the color cut $u - r = 0.8$, which we adopt to separate galaxy samples.

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

Figure 5. Luminosity functions in the $i$-band for the redshift intervals $0.6 < z < 0.8$ (left panel), $0.8 < z < 1.0$ (middle panel), and $1.0 < z < 1.2$ (right panel). The black lines show the best fitting Schechter functions for the total luminosity functions; the blue and red curves show the Schechter functions for the two SED types. (A color version of this figure is available in the online journal.)

3.3. Errors and the Density Profile Fit

We estimate the statistical errors of our correlation measurements using the bootstrap method (more details and different methods for realistic error calculation are discussed in Norberg et al. 2009). We generate $N = 50$ bootstrap quasar samples. The objects in each bootstrap sample are randomly picked from our original quasar sample, allowing for multiple selection of the same objects. We then compute $n(r_p)$ for each sample using the method discussed in Section 3.1. The errors on $n(r_p)$ are given by the standard deviation of the measurements among these bootstrap samples. After obtaining the covariance matrix $M_{jk}$, we can derive the covariance matrix $M_{jk}$ by

$$M_{jk} = \frac{1}{N-1} \sum_{s=1}^{N} \left[ \langle n(r_p^j) \rangle - \langle n(r_p^j) \rangle \right] \times \left[ \langle n(r_p^k) \rangle - \langle n(r_p^k) \rangle \right] \times \left[ M_{jk}^{-1} \times \langle n(r_p^j) \rangle - \langle n(r_p^j) \rangle \right],$$

where $n(r_p^j)$ is the galaxy number density at the $j$th radius bin for the $s$th bootstrap sample and $\langle n(r_p^j) \rangle$ is the average over all of the bootstrap samples at the $j$th radius bin (e.g., Miyaji et al. 2007). After obtaining the covariance matrix, we fit the density profile using Equation (3) by minimizing the correlated $\chi^2$ values:

$$\chi^2 = \sum_{j=1}^{N_{\text{bins}}} \sum_{k=1}^{N_{\text{bins}}} \left[ n(r_p^j) - n_{\text{model}}(r_p^j) \right] \times M_{jk}^{-1} \times \left[ n(r_p^k) - n_{\text{model}}(r_p^k) \right],$$
Table 1

| Quasar Subsample | Redshift Interval | Median $z$ | Number of Objects | Median $M_i$ | Median $M_{BH}$ | Selection |
|------------------|------------------|------------|------------------|--------------|----------------|-----------|
| z1               | 0.6–0.8          | 0.70       | 687              | −23.31       |                |           |
| z2               | 0.8–1.0          | 0.89       | 678              | −23.87       |                |           |
| z3               | 1.0–1.2          | 1.09       | 935              | −24.35       |                |           |
| z1D              | 0.6–0.8          | 0.69       | 541              | −23.14       |                |           |
| z2D              | 0.8–1.0          | 0.88       | 389              | −23.54       |                | $M_i > -24.0$ |
| z3D              | 1.0–1.2          | 1.06       | 243              | −23.78       |                |           |
| z1B              | 0.6–0.8          | 0.73       | 146              | −24.40       |                |           |
| z2B              | 0.8–1.0          | 0.91       | 289              | −24.62       |                | $M_i < -24.0$ |
| z3B              | 1.0–1.2          | 1.10       | 692              | −24.60       |                |           |
| z1L              | 0.6–0.8          | 0.69       | 449              | −23.23       | $1.5 \times 10^8$ |           |
| z2L              | 0.8–1.0          | 0.88       | 294              | −23.79       | $1.9 \times 10^8$ |           |
| z3L              | 1.0–1.2          | 1.08       | 362              | −24.19       | $2.0 \times 10^8$ |           |
| z1H              | 0.6–0.8          | 0.71       | 212              | −23.54       | $5.9 \times 10^8$ |           |
| z2H              | 0.8–1.0          | 0.90       | 304              | −24.19       | $6.2 \times 10^8$ |           |
| z3H              | 1.0–1.2          | 1.09       | 559              | −24.52       | $7.4 \times 10^8$ |           |
| Blue             | 0.6–1.2          | 0.93       | 764              | −24.56       |                |           |
| Green            | 0.6–1.2          | 0.94       | 769              | −24.13       |                |           |
| Red              | 0.6–1.2          | 0.94       | 767              | −23.97       |                |           |

where $n(r_p)$ is the density profile derived from observational data while $n_{\text{model}}(r_p)$ is a fitting curve. Then, we can get the cross-correlation amplitude, $r_0$, and the slope, $\gamma$.

### 3.4. Cosmic Variance

Cosmic variance is the uncertainty in observational estimates of the number density of galaxies in finite volumes, arising from underlying large-scale density fluctuations. It can be significant, especially for deep “pencil beam” surveys. COSMOS, used to estimate the number density ($\rho_0$) of galaxies in this work, is one example of a comparatively wide field. The $\text{zCOSMOS}$ and AzTEC/COSMOS fields, subsets of COSMOS, are known to have $\sim 3\sigma$ positive fluctuations in the redshift range $z \leq 1.1$ (Meneux et al. 2009; Austermann et al. 2009). Moster et al. (2011) predicted cosmic variance of COSMOS for a given galaxy population from cold dark matter theory and the galaxy bias. In the analysis of stellar mass functions in the COSMOS field, they used stellar population synthesis models to convert luminosity into stellar mass and obtained the masses of galaxies with $i_{\text{Subaru}} < 25$ (Drory et al. 2009; Ilbert et al. 2010). The luminosity functions suggest that galaxies at the low-luminosity end are the dominant component in a magnitude-limited sample. The apparent magnitudes of galaxies are $17.0 < i < 23.2$ in our following calculation; the absolute magnitudes at $1.0 < z < 1.2$ are more luminous ($\sim 1$ mag) than those at $0.6 < z < 0.8$. In contrast with the stellar masses of the COSMOS galaxies, the mean stellar masses of different galaxy samples in our magnitude range with different redshifts and colors are in the mass range of $10^{9.2} M_\odot < m_\star < 10^{11} M_\odot$. High-redshift red galaxies have higher masses than low-redshift blue galaxies.

Cosmic variance with common redshift bins gradually decreases with redshift from $\tilde{z} = 0.7$ to $\tilde{z} = 1.1$ with a redshift bin size $\Delta z = 0.2$ and increases with galaxy stellar mass from $m_\star = 10^{9.25} M_\odot$ to $m_\star = 10^{10.75} M_\odot$ with a mass bin size $\Delta \log(m_\star/M_\odot) = 0.25$ (Table 2 in Moster et al. 2011). The variance ranges between $\sim 8\%$ and $\sim 12\%$; the mean value is $\sim 9.5 \pm 1.1\%$. Cosmic variance cannot impact the dependence of clustering on quasar properties because the comparisons are made in the same volume and same galaxy sample. If COSMOS is really in an overdense region, the real correlation amplitudes are somewhat larger than we present in this work. However, cosmic variance is considered in the study of the dependence on galaxy properties and clustering redshift evolution. When COSMOS has $\sim 10\%$ cosmic variance, on average, the variance of $r_0$ is $\sim 5\%$, less than the measurement errors (Tables 2 and 3). The strength of quasar–galaxy clustering still depends on various properties, but the confidence levels of these correlations are somewhat reduced.

### 4. QUASAR–GALAXY CLUSTERING

#### 4.1. Dependence on Redshift

In order to investigate whether clustering is dependent on redshift, we investigate the clustering between galaxies of $i$-band apparent magnitudes in the range of $(17.0, 23.2)$ (denoted as the “all galaxies” sample) and quasar subsamples at different redshifts. We divide the quasar sample into three redshift intervals: 687 quasars at $0.6 < z < 0.8$ ($z1$ sample), 678 quasars at $0.8 < z < 1.0$ ($z2$ sample), and 935 quasars at $1.0 < z < 1.2$ ($z3$ sample). The median redshifts of these subsamples are $0.70, 0.89$ and $1.09$, and the median absolute magnitudes in the $i$-band are $-23.31, -23.87$ and $-24.35$ mag, respectively. A summary of the subsample parameters can be found in Table 1. For each quasar subset, we first calculate $n_{\text{bg}}$ and $\rho_0$ (see Section 3.1), which will be used as fixed values in the density profile fit procedure. We then calculate the average density profile $n(r_p)$ of galaxies as a function of projected distance in the co-moving scale between $0.05 \leq r_p \leq 20 h^{-1}$ Mpc from quasars as described in Section 3.1. The results are shown in Figure 6. As one can see, the clustering signals are detected in all redshift bins. The best-fit results ($r_0$ and $\gamma$) are listed in Table 2. For comparison, we also show the density profile for a random quasar sample at redshifts of $0.6 < z < 0.8$ (see Section 3.1 for the methodology for constructing the random quasar sample) in the bottom-right panel of Figure 6. Density is constant with radius, suggesting that the clustering associated with the quasars is real.
Initially, we independently fit the density profiles in different redshift bins with $r_0$ and $\gamma$ as free parameters. We found that $r_0$ increased significantly with redshift and that $\gamma$ was a constant to within 1σ (Table 2). To better constrain the amplitude, we simultaneously fit over the three redshift bins while forcing $\gamma$ to have the same value. We obtained the following fit results: a power-law index of 2.10 and a correlation amplitude $r_0 = 3.68 \pm 0.44$ h$^{-1}$ Mpc for the $z1$ subsample at $0.6 < z < 0.8$; $4.91 \pm 0.40$ h$^{-1}$ Mpc for the $z2$ subsample at $0.8 < z < 1.0$, and $5.96 \pm 0.95$ h$^{-1}$ Mpc for the $z3$ subsample at $1.0 < z < 1.2$ (Table 2), consistent with a fit where $\gamma$ was left as a free parameter. The galaxies of a given apparent magnitude around a high-redshift quasar are more luminous than those with the same apparent magnitude around a low-redshift counterpart. Therefore, we found that the clustering of galaxies increases with galaxy luminosity also leads to a redshift dependence. To disentangle this effect, we use galaxies in apparent magnitude ranges of $17.0 < i < 22.0$ and $18.2 < i < 23.2$ to calculate the cross-correlation with the $z1$ and $z3$ subsamples, respectively; the absolute magnitudes of the galaxies are very similar in these two redshift bins. The resultant $r_0$ values are $3.42 \pm 0.51$ h$^{-1}$ Mpc and $5.77 \pm 0.92$ h$^{-1}$ Mpc, respectively. Obviously, the redshift dependence of quasar–galaxy clustering is still significant although it is somewhat weak.

To check the effects of galaxy sample incompleteness, we selected a galaxy sample using a more conservative photometric depth ($i_{th} = i_{th} - 0.2$ mag). We then recalculated the CCFs between the three quasar subsamples and galaxies in the same apparent magnitude range, i.e., $17.0 < i < 23.2$. The results are $r_0 = 3.73 \pm 0.53$ h$^{-1}$ Mpc, $5.03 \pm 0.47$ h$^{-1}$ Mpc, and $5.97 \pm 1.02$ h$^{-1}$ Mpc with $\gamma = 2.10$ for the three subsamples. We also use this new sample to recalculate the clustering between the different quasar subsamples and galaxy subsamples shown below; all the new results are consistent with those presented in this paper. Therefore, our choice of photometric depth do not influence the results significantly. In addition, the maximum projected distance is fixed to 20 h$^{-1}$ Mpc in this work. It is a factor of three times larger than the typical value of $r_0$. In principle, it is sufficient for the determination of the correlation amplitude. To be safe, we measured $r_0$ and $\gamma$ based on the density profile with different maximum projected distances. Both $r_0$ and $\gamma$ changed very little.

Because of the shallow photometric depth of Stripe 82, we cannot measure quasar–galaxy clustering at higher redshifts. But the clustering measurements at higher redshifts can be used to inspect our method. Since the galaxies at high redshifts cannot be detected, all the galaxies and stars in the Stripe 82 calibrated object catalog are background objects ($n_{bg}$ in Equation (3)) and $w(r_p) = 0$. We selected 683 quasars with redshifts ranging from 2.0–2.2 as the high redshift quasar sample. We show the projected galaxy number density ($n_{bg}$) as a function of projected distance ($r_p$) in Figure 7. The density is constant with radius, thus confirming the reliability and robustness of our method.

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**Figure 6.** Averaged galaxy number density as a function of projected distance from the quasar for each redshift interval. The filled circles show the galaxy number density for each quasar redshift subsample, the dashed lines indicate the background counts ($n_{bg}$), and the solid lines indicate the best fit. The right bottom panel shows the random quasar sample in the redshift interval $0.6 < z < 0.8$.

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

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**Table 2**

Cross-correlation Results between Quasar Subsamples with Different Redshifts and the “All Galaxies” Sample

| Samples         | $r_0 (h^{-1} \text{Mpc})$ | $\gamma$ | $r_0(\gamma=2.10) (h^{-1} \text{Mpc})$ | $\rho_0 (h^{-1} \text{Mpc}^{-3})$ | $n_{bg} (h^{-1} \text{Mpc}^{-2})$ |
|-----------------|---------------------------|----------|---------------------------------------|---------------------------------|-------------------------------|
| z1-all galaxies | $3.49 \pm 0.89$           | $2.14 \pm 0.21$ | $3.68 \pm 0.44$                      | $9.09 \pm 0.07$                 | $59.47 \pm 0.15$             |
| z2-all galaxies | $4.91 \pm 0.75$           | $2.09 \pm 0.17$ | $4.91 \pm 0.40$                      | $4.95 \pm 0.04$                 | $39.28 \pm 0.09$             |
| z3-all galaxies | $6.00 \pm 1.90$           | $2.10 \pm 0.25$ | $5.96 \pm 0.95$                      | $1.06 \pm 0.01$                 | $29.75 \pm 0.08$             |
4.2. Dependence on Quasar Properties

In this section, we analyze the dependence of quasar–galaxy clustering on luminosity, black hole mass, and the optical color of the quasars. The galaxy sample used here is composed of all galaxies with $i$-band apparent magnitudes in the range of $(17.0, 23.2)$. The information for various quasar subsamples is listed in Table 1.

To examine the dependence of clustering on the luminosity of quasars, we divided all quasars at $0.6 < z < 1.2$ into luminous and faint groups of equal size. Since the $\gamma$ parameter is independent of redshift, we fixed it at 2.10 when fitting the density profile. We obtain $r_0 = 4.47 \pm 0.35$ h$^{-1}$ Mpc for faint quasars and $5.52 \pm 0.37$ h$^{-1}$ Mpc for luminous quasars. The difference is significant at the 2.1$\sigma$ level. However, this dependence can be induced by the redshift dependence of clustering because the median redshifts of the faint and luminous subsamples are $z = 0.82$ and $1.04$, respectively. To break the redshift-luminosity degeneracy, we split the $z1$ quasar sample (the quasar sample at $0.6 < z < 0.8$) into $z1B$ and $z1D$ subsamples (Table 1, panel (b) of Figure 1). The $z1D$ subsample consists of 541 quasars in the range $-24.0 < M_i < -22.0$ and the $z1B$ subsample is made up of 146 quasars in the range $-26.5 < M_i < -24.0$. The median $z$ of the two subsamples is very similar. The clustering amplitudes are $r_0 = 3.76 \pm 0.40$ h$^{-1}$ Mpc and $3.64 \pm 0.90$ h$^{-1}$ Mpc for the $z1B$ and $z1D$ subsamples, respectively (Table 3). Similar results are obtained for the other two redshift bins (Table 3). Therefore, we do not detect any significant dependence of quasar–galaxy clustering on quasar luminosity within our uncertainties. This finding is in good agreement with recent results derived using very different methods (Crook et al. 2005; Adelberger & Steidel 2005; Lidz et al. 2006; Myers et al. 2006; Shirasaki et al. 2011; Shen 2009; Shen et al. 2012).

Next, we study the dependence of clustering on the black hole mass of quasars. The black hole masses for most quasars are calculated using a black hole mass formalism based on the broad Mg II line and the monochromatic luminosity at 3000 Å. For a small number of quasars where the Mg II spectral regime is not observable, the masses are estimated using the broad H$\beta$ line and the 5100 Å monochromatic luminosity. Both Mg II- and H$\beta$-based $M_{\text{BH}}$ estimators come from Wang et al. (2009). We take the median $M_{\text{BH}}$ value of the whole sample, $3.5 \times 10^8 M_\odot$, as the arbitrary value $M_\text{BH}$, and divide the $zj$ subsamples into two subsamples, $zjH$ and $zjL$, each of which consists of quasars with $M_{\text{BH}} > M_\text{BH}$ and $M_{\text{BH}} < M_\text{BH}$ (see panel (c) of Figure 1). As shown in Table 3, $r_0$ is larger for massive black hole mass in each redshift bin at a significance of $\sim 1\sigma$.

Finally, we examine the dependence of clustering on the optical color of quasars. The continuum slope $\beta_{3.0-4.0\text{K}}(f_{\lambda} \propto \lambda^{\beta_{3.0-4.0\text{K}}})$ is measured from the Galactic reddening-corrected quasar spectrum between $\sim 3000$ Å and $\sim 4000$ Å in the rest-frame. The two continuum windows, $[3010, 3040]$ Å and $[4210, 4332]$ Å, are chosen to avoid strong Fe II multiplets shortward of 3000 Å and possible starlight contributions longward of 5000 Å in some quasars. Thus, $\beta_{3.0-4.0\text{K}}$ is used as a fair measurement of the continuum slope. We calculate $\tilde{\beta}(z)$, the median $\beta_{3.0-4.0\text{K}}$ as a function of redshift, and divide the quasars into “Blue,” “Green,” and “Red” quasar subsamples according to their relative optical colors ($\beta_{3.0-4.0\text{K}} - \tilde{\beta}(z)$) (see panel (d) of Figure 1). We select different optical color subsamples in this way to make sure that these subsamples have similar redshift distributions. A summary of these subsamples is listed in Table 1. As shown in Table 3, the correlation amplitude is marginally larger ($\sim 2.3\sigma$) for blue quasars than for red quasars. The blue quasars are slightly more luminous than the red quasars (Table 1). Because we do

![Figure 7. Averaged galaxy number density as a function of projected distance from the quasar in the redshift interval $2.0 < z < 2.2$. The dashed line has a value equal to 13.02 ($h^{-1}$ Mpc)$^{-2}$. (A color version of this figure is available in the online journal.)](image)
not find significant evidence for a dependence of clustering on quasar luminosity, the color dependence of quasar–galaxy clustering is not ascribed to differences in luminosity. We cross-matched our quasar sample with objects with Galaxy Evolution Explorer (Morrisssey et al. 2007) and UKIDSS (Lawrence et al. 2007) observations within a 2° position offset, and found 1211 and 1869 quasars, respectively. We then calculated these objects’ NUV–optical and optical–IR colors. The clustering measurements show that a color dependence can also be detected based on colors in other wavebands.

### 4.3. Dependence on Galaxy Properties

Galaxy clustering depends on galaxy properties, such as color (e.g., Zehavi et al. 2004, 2005; Coil et al. 2004; Li et al. 2006) and luminosity (e.g., Zehavi et al. 2004, 2005; Li et al. 2006) in the local or intermediate redshift (0.2 < z < 1) universe. Red/bright galaxies are much more strongly clustered than blue/faint galaxies. The cross-correlations between quasars and galaxies also depend on galaxy properties. In this section, we will use the z1, z2 and z3 quasar samples to examine how the correlation amplitude changes with galaxy luminosity or spectral type. These findings will provide additional constraints on galaxy and AGN co-evolution models. Here again, we fix the slope to γ = 2.10 during the fitting procedure.

First, in order to investigate the dependence on galaxy magnitude, we divide the galaxies into two apparent magnitude bins. The magnitude threshold used to split the galaxy sample changes depending on which quasar sample is employed. For example, as we calculate the density profile of bright and faint galaxies around the z1 quasar sample, the apparent magnitude threshold we adopt is i = 21.0. When we calculate the density around the z3 sample, the magnitude threshold increases to 22.0 (see Table 3). The magnitude threshold is chosen such that the corresponding absolute magnitude is approximately the same after taking into consideration the average k-correction in each redshift bin; the values of the k-correction are roughly estimated based on the mean galaxy SED. All of the results are shown in Table 3. The correlation amplitudes with faint galaxies are very similar to those with all galaxies (Table 1), because the number of faint galaxies is much larger than the number of luminous galaxies. In all three redshift bins, the correlation amplitudes with luminous galaxies are about two times larger than those with faint galaxies. The differences are significant at the 3.7σ, 3.6σ, and 3.8σ levels, respectively. In addition, r0 significantly increases with redshift, especially for luminous galaxies, consistent with our previous results.

We further explore how quasar–galaxy clustering depends on galaxy SEDs. We take u − r = 0.8 as the color criterion and divide the photometric galaxies into red and blue galaxy samples (see Section 3.2). We then measure the cross-correlation between z1, z2, and z3 quasar samples and these two galaxy samples (17.0 < i < 23.2). The results are shown in Table 3. For blue galaxies, the correlation amplitude increases remarkably with redshift (Figure 8). However, the correlation amplitude for red galaxies varies only marginally. There is a significant trend that the correlation amplitude is larger for blue galaxies than it is for red galaxies. The small scale slope of the correlation function is known to vary with galaxy color; quasar–blue-galaxy clustering has a slightly steeper slope than of quasar–red-galaxy clustering (e.g., Norman et al. 2009) and the fixed increases the difference in the amplitude between the clustering of quasars with both galaxy type. Quasar–blue-galaxy clustering shows a greater amplitude and quasar–red-galaxy clustering shows a smaller amplitude than the result we obtained with slope as a free parameter.

### 4.4. Comparisons with Other Results

Generally, different clustering measurements cannot be compared directly unless the studies used the same luminosity/redshift range of AGNs/quasars and the same luminosity/redshift range of galaxies. Compared to this work, (most) other AGN samples have much lower luminosities and (most) other galaxy samples have much higher luminosities used in the measurements of AGN–galaxy CCFs. However, the trend of the clustering strength changing with AGN/quasar or galaxy properties obtained in other studies can be used to check the clustering dependence obtained in this work. Furthermore, comparing our work with other studies can also elucidate potential reasons for our different results. In addition, these comparisons can shed light on our results that are similar to the findings of other authors (the independence of AGN/quasar clustering on galaxy properties).

At 0.6 < z < 0.8, the cross-correlation amplitude derived in this paper is consistent with that derived from infrared-selected and X-ray-selected AGNs in the AGN and Galaxy Evolution Survey (AGES) using a spectroscopic galaxy sample over a smaller area (Hickox et al. 2009). Our results are also consistent with a sample of Subaru photometric galaxies and a faint AGN sample over a broader redshift range (Shirasaki et al. 2011). Finally, our results also agree with the analysis of X-ray AGNs in the Chandra Deep Field North (Gilli et al. 2005). However, these amplitudes are significantly smaller than recent results based on the cross-correlation of quasars with spectroscopic luminous red galaxies (LRGs; Norman et al. 2009, hereafter N09; Padmanabhan et al. 2009; Mountrichas et al. 2009) and the AGN–galaxy correlation in the Chandra Deep field South (Gilli et al. 2005). In addition, these authors derived a smaller power-law index ($γ$ ~ 1.65–1.83).

These differences may be caused by three factors: different galaxy luminosities are involved, different weights are employed toward the large and small scales, and cosmic variance. First, the LRGs in these samples are more luminous and massive than in our galaxy samples. A large clustering amplitude seems consistent with our results that luminous galaxies tend to be strongly clustered around quasars. In fact, their clustering amplitudes are similar to those of the luminous galaxies.

![Figure 8. Cross-correlation amplitude as a function of redshift.](image-url)
presented in this work. Secondly, our method is more sensitive to small-scale overdensities than are the methods using spectroscopic galaxy samples because the fluctuation of a large number of background/foreground sources will overwhelm the signal in the outer region. In addition, Meneux et al. (2009) showed that the flux limit will tend to weaken the clustering measurement at small scales because of mass incompleteness in a flux-limited sample. Since our photometric sample is deeper than these LRG spectroscopic samples, the effect of mass incompleteness tends to be smaller. As illustrated by McBride et al. (2011) in the LasDamas beta mock sample for the local universe, \( w(r_g) \) has a steeper slope of around 2.06 on scales of 0.2 to 1.0 \( h^{-1} \) Mpc than on scales of 2–10 \( h^{-1} \) Mpc (\( z \approx 1.70 \)). Thus, most of the quasar–galaxy clustering signal we measure probably comes from scales smaller than 1 \( h^{-1} \) Mpc, although we measure up to 20 \( h^{-1} \) Mpc. In other words, we probably only measure the clustering in the one-halo term. Thirdly, the large difference in the two Chandra deep fields is likely due to cosmic variance (Meneux et al. 2009), although different survey depths may also explain some of the differences.

At \( z \approx 1 \), the clustering amplitude for the entire quasar sample in Stripe 82 is significantly larger than that obtained by C07 for optically selected quasars in AGES and galaxies in the DEEP2 survey, smaller than the AGN sample of Shirasaki et al. (2011), but similar to the X-ray-selected AGNs in AGES (Coil et al. 2009). C07 measured \( r_0 = [2.95, 3.56] h^{-1} \) Mpc and \( r_0 = 1.83 \) over distance scales of 0.05 to 10 \( h^{-1} \) Mpc by cross-correlating DEEP2 galaxies at \( 0.7 < z < 1.4 \) with different quasar samples identified in SDSS and DEEP2. Shirasaki et al. (2011) obtained a very similar correlation amplitude between bright quasars and Subaru deep photometric data. When \( r_0 \) is fixed at 1.83, we obtain a much higher correlation amplitude of \( 5.31 \pm 0.49 h^{-1} \) Mpc and \( 5.67 \pm 1.04 h^{-1} \) Mpc. Because the luminosity ranges of both quasars (\( M_B < -22 \)) and galaxies (\( R_{AB} < 24.2 \)) are similar to our samples, the reason for the discrepancy is not easily understood; it is likely due to the different systematics of the methods. Bornancini & García Lambas (2007) found a larger correlation amplitude (\( r_0 = 5.4 \pm 1.6 h^{-1} \) Mpc and \( r_0 = 1.94 \pm 0.10 \)) in the DEEP2 fields. Their amplitude is similar to the correlation of red galaxies with quasars in our sample. Because Bornancini & García Lambas (2007) used distant red galaxies at \( 1 < z < 2 \) with a color cut \( J - K_s > 2.3 \), their results are fully consistent with ours.

The fact that clustering amplitude increases with black hole mass but not quasar luminosity in the redshift range considered is broadly consistent with previous results. Hickox et al. (2009) analyzed the cross correlation between AGNs and galaxies based on AGES data at \( 0.25 < z < 0.8 \). AGNs selected with radio, X-ray detection, and infrared colors show different properties, and the radio- and infrared-selected AGNs have similar black hole masses to our high-\( M_{BH} \) and low-\( M_{BH} \) samples, respectively. The clustering amplitude of the radio-selected AGNs is significantly larger than that of the infrared-selected AGNs, indicating an increasing clustering amplitude with black hole mass. Coil et al. (2009) compared the clustering amplitudes of X-ray AGNs and quasars in C07 and found that X-ray AGNs at \( z \approx 1 \) are more clustered than quasars with a 2.6σ significance. Meanwhile, the X-ray AGNs have higher black hole mass than quasars. In summary, the clustering dependence on black hole mass is confirmed in other works. Admittedly, the AGN samples in these works have significantly different properties expect for black hole mass (i.e., radio properties, IR optical, or X-ray selection, absorbed or unabsorbed, and broad or narrow emission-lines). We also cannot rule out the possibility of increasing CCF clustering with black hole mass due to selection or other properties (non-\( M_{BH} \)) of AGN samples.

Previous studies have shown that the quasar ACF and the AGN–galaxy CCF clustering amplitude increase with redshift. Croom et al. (2005) divided over 20,000 2QZ objects into 10 redshift intervals with effective redshifts ranging from \( z = 0.53 \) to 2.48. They measured the redshift-space two-point correlation functions and found that the quasar clustering amplitude increases with redshift such that the integrated correlation function \( \xi(z = 0.53) = 0.26 \pm 0.08 \) and \( \xi(z = 2.48) = 0.70 \pm 0.17 \). Myers et al. (2006) also found an increasing clustering amplitude with redshift by calculating the projected angular clustering of \( \sim 80,000 \) photometric quasars in SDSS. Directly related to this work, Hopkins et al. (2007) confirmed their conclusion from comparing the observed clustering of quasars and galaxies as a function of redshift (dotted line in Figure 8). Our measurement of cross-correlation over a much smaller redshift range and on smaller scales shows the same trend.

One of the most surprising findings is that the cross-correlation amplitude depends strongly on galaxy color. C07 found that quasars reside in regions more similar to the mean overdensity of blue galaxies than red galaxies when they looked at the correlation function of the SDSS quasars with the DEEP2 galaxies at \( z \approx 1 \). N09 separated the 2SLAQ LRG sample, which contains nearly 15,000 LRGs with magnitudes more luminous than \( i = 19.8 \) with a median redshift of \( \sim 0.52 \), into two populations of blue and red galaxies using the color cut \( g - r = 1.6 \). They found the projected two point correlation to have a clustering amplitude of \( r_0 = 7.3 \pm 0.7 h^{-1} \) Mpc and \( r_0 = 4.9 \pm 0.7 h^{-1} \) Mpc on scales from 0.7 to 27 \( h^{-1} \) Mpc for the two populations. Those quasars have a stronger correlation amplitude with the blue population than with the red population. Although our color-selected method and that of N09 are different, the quasar correlation amplitude trend with blue and red galaxies is consistent in the two studies. Furthermore, we found that the correlation amplitude with blue galaxies increases strongly with redshift while that with the red galaxies varies only marginally. Note that the redshift distributions of blue and red galaxies can affect the clustering dependence on galaxy color. However, the galaxy sample we used is the Stripe 82 photometric sample, where the redshifts of these galaxies are not known.

5. DISCUSSION

In the local universe, the clustering of galaxies, as measured by many authors, is \( 5–7 h^{-1} \) Mpc (Hawkins et al. 2003; Zehavi et al. 2005; Li et al. 2007; Ma et al. 2009). Measurements up to \( z = 2 \) suggest that the clustering length increases with redshift. In the redshift range of this paper, the clustering amplitudes are around \( 5–9 h^{-1} \) Mpc, depending on the mass of the galaxies (Pollo et al. 2006; Coil et al. 2006; Meneux et al. 2008; Magliocchetti et al. 2008; Foucaud et al. 2010). The clustering amplitudes of galaxies around quasars derived in this paper are similar to these values, and also have the same dependence on redshift. These results imply that these quasars are located in a DMH which has similar mass to that occupied by typical galaxies in these samples with stellar masses larger than \( 10^{10} M_\odot \).

Evidence has been mounting for a strong link between black holes and the mass of the bulge components of galaxies (e.g., Magorrian et al. 1998). In Halo Occupation Distribution (HOD)
models, the masses of these bulges are correlated with the mass of the halo (e.g., Jing et al. 1998; Yang et al. 2003). Therefore, quasars with larger $M_{BH}$ are located in relatively larger host DMHs. Indeed, Ferrarese (2002) found that the mass of the central black hole is plausibly correlated with that of its host halo (the total gravitational mass of its host galaxy). Furthermore, it is well known that halo clustering is dependent on halo mass (e.g., Mo & White 1996). Therefore, it is expected that clustering around more massive quasars is stronger than that around lower mass quasars. Our findings are consistent with this hypothesis.

The quasar luminosity is determined by the black hole mass and the Eddington ratio. Thus, for a given Eddington ratio, the luminosity is proportional to the black hole mass. If all quasars are accreting at a similar Eddington ratio or close to the Eddington limit, we will observe a significant correlation of clustering strength with the quasar luminosity. If the luminosity of the quasar sample is driven largely by Eddington ratios, the luminosity dependence will be quite weak, or even disappear. Hopkins et al. (2007) discussed the connection between the observed quasar-to-galaxy cross correlation and luminosity. They also considered that the variation in Eddington ratios at a given black hole mass is major driver of the weak dependence on quasar luminosity, and that the clustering is much more strongly correlated with galaxy luminosity than it is with quasar luminosity (also see Coil et al. 2009).

We also found that the quasar–galaxy clustering depends significantly on quasar color, in the sense that blue quasars are more strongly clustered than red quasars. This result strongly implies that AGN activity is influenced by large scale environment, although the underlying physics is unclear. Hickox et al. (2011) measured the spatial clustering of luminous mid-infrared selected obscured and unobscured quasars in the redshift range $0.7 < z < 1.8$. Their results indicate that the cross-correlation of obscured quasars with galaxies is somewhat stronger than that for the unobscured quasars. Generally, the obscured quasars are possibly redder than the unobscured quasars. The measurements of Hickox et al. (2011) do not agree with this work. However, it must be pointed out that the selection boundary of the obscured and unobscured quasars is the optical–IR color selection $R - [4.5\,\mu m]_{IRAC\,\,\,band} = 6.1$ (see Hickox et al. 2007, 2011) for details about the mid-infrared selected quasar sample). We also estimated the similar optical–IR colors for our quasar color. We split the quasars into two black hole mass subsamples at $M_{BH} = 3.5 \times 10^{8} M_{\odot}$ for each redshift bin. The clustering amplitude is slightly larger for quasars with more massive black hole mass in each redshift interval. We also find that the clustering amplitude depends on the color of the quasar; the amplitude is significantly larger (2.3$\sigma$) for blue quasars than it is for red quasars. However, a dependence on quasar luminosity is absent in each redshift bin.

3. There is a strong dependence of clustering amplitude on the SED type of galaxies, with blue galaxies being more strongly clustered around quasars than red galaxies at the 3.4$\sigma$ confidence level.

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