THE EVOLUTION OF THE DUSTY TORUS COVERING FACTOR IN QUASARS

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ABSTRACT

We have assembled a large sample of 5996 quasars at $2.0 \leq z \leq 2.4$ (high-$z$) or $0.7 \leq z \leq 1.1$ (low-$z$) from the Sloan Digital Sky Survey (SDSS) ninth and seventh data release and quasar catalogs. The spectral energy distributions of quasars were constructed by collecting WISE, UKIDSS, and GALEX photometric data in addition to SDSS data, from which the IR luminosity at $1–7 \mu$m and bolometric luminosity at 1100 Å–1 μm were calculated. A red tail is clearly seen in the distribution of the spectral index over 1100 Å–1 μm for both the high-$z$ and low-$z$ sources; this tail is likely due to red or reddened quasars. The covering factor (CF) of the dusty torus is estimated as the ratio of the IR luminosity to the bolometric luminosity. We find significant anti-correlations between the CF and the bolometric luminosity, in both the high-$z$ and low-$z$ quasars; however, these two groups follow different tracks. At overlapping bolometric luminosities, the CF of high-$z$ quasars is systematically larger than those of low-$z$ quasars, implying an evolution of the CF with redshift.

Key words: catalogs – galaxies: active – infrared: general – quasars: general

Online-only material: color figures

1. INTRODUCTION

In the unification scheme of active galactic nuclei (AGNs), the dusty torus plays an important role in the diversity of observational phenomena (Antonucci 1993; Urry & Padovani 1995). In Type 1 AGNs, observers can directly see the central nuclei and broad line region; these features are however obscured by the dusty torus in Type 2 AGNs. Although a lot of effort has been made, still little is known about the geometry, dynamics, and evolution of dusty tori (Elitzur 2008).

The covering factor (CF) of the dusty torus can be estimated by the fraction of Type 2 AGNs in certain samples, and a mean value of $\sim 0.6$ has been found (Lawrence & Elvis 2010). In the spectral energy distributions (SEDs) of AGNs, generally two bumps can be clearly seen (Elvis et al. 1994). The first bump in the optical/ultraviolet region is usually believed to be thermal emission from the accretion disk, while the second bump in the infrared region is thought to be reprocessed emission from the dusty torus from the absorption of central nuclei emission. Therefore, the CF of the dusty torus can be measured by the ratio of the torus infrared luminosity to the bolometric luminosity.

Largely limited by available IR data, the CF has been recently investigated only for a few quasar samples with rather limited source numbers (e.g., Cao 2005; Maiolino et al. 2007). Significant anti-correlations have been found between the CF and the bolometric luminosity, and the CF and the black hole mass. The breakthrough came with the all-sky data release from the Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010). The WISE photometric data in the near- and mid-infrared bands can be used to study the IR emission as well as the dust CF for large AGN samples (Mor & Trakhtenbrot 2011; Calderone et al. 2012; Ma & Wang 2013; Roseboom et al. 2013). However, previous works are all at $z < 2$, and AGNs at low and high redshifts were usually mixed together (Maiolino et al. 2007; Mor & Trakhtenbrot 2011; Roseboom et al. 2013); evolution effects cannot be ignored in these samples. Although some works investigated the CF in quasars in narrow redshift ranges using WISE data (Calderone et al. 2012; Ma & Wang 2013), there are a lack of studies comparing the CF between quasars at high and low redshifts. The recent quasar catalog from the Sloan Digital Sky Survey (SDSS) data release nine (DR9) consists of a large number of quasars at $z > 2$ (Pâris et al. 2012), which enables us to explore not only the CF at $z > 2$, but also the evolution of the CF by making comparisons with $z < 2$ quasars from previous SDSS quasar catalogs. Moreover, the dependence of the CF on luminosity can be further studied in narrow redshift ranges by separating the coupled effects of luminosity and redshift.

The layout of this paper is as follows. In Section 2, we describe the source sample; the analysis of the CF is outlined in Section 3. Section 4 includes the discussion, and in the last section, we draw our conclusions. The cosmological parameters $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.3$, and $\Omega_{\Lambda} = 0.7$ are used throughout the paper, and the spectral index $\alpha$ is defined as $f_\nu \propto \nu^\alpha$, where $f_\nu$ is the flux density at a frequency $\nu$.

2. SAMPLE CONSTRUCTION

2.1. Multi-wavelength Surveys

With the aim of detecting baryon acoustic oscillations (BAOs), the five-year Baryon Oscillation Spectroscopic Survey (BOSS; Dawson et al. 2013) of SDSS-III (Eisenstein et al. 2011) will obtain spectra of 1.5 million galaxies and over 150,000 quasars at $z > 2.15$ in 10,000 deg$^2$. The BAO signal will be investigated from the spatial distribution of luminous red galaxies at $z \sim 0.7$ and H$\upalpha$ absorption lines in the intergalactic medium (IGM) as detected in the Ly$\alpha$ forest of quasar spectra at $z \sim 2.5$ (see Dawson et al. 2013 for details).

The SDSS Data Release 9 Quasar (DR9Q) catalog was constructed from the first two years of BOSS operations and includes 87,822 quasars detected over 3275 deg$^2$, spectroscopically confirmed via visual inspection. The quasars have luminosities $M_i(z = 2) < -20.5$ and display either at least one emission line with a FWHM larger than 500 km s$^{-1}$ or, if not, an interesting/complex set of absorption features (Pâris et al. 2012). The robust identification and
redshift measurements were performed for each quasar from the spectra over the wavelength region 3600–10500 Å at a spectral resolution of 1300 < R < 2500. The catalog presents the largest sample of quasars at z ≥ 2.15, with a total of 61,931 objects. In addition to the five-band (u, g, r, i, z) magnitudes with a typical accuracy of 0.03 mag, the catalog contains multi-wavelength data such as X-ray, ultraviolet, near-infrared, and radio observations when available (see Pâris et al. 2012 for details).

The DR9Q catalog includes fainter objects than in SDSS-I/II, since a fainter limiting magnitude in the target selection was adopted to obtain a high quasar surface density as needed since a fainter limiting magnitude in the target selection was adopted to obtain a high quasar surface density as needed when available (see Pâris et al. 2012 for details).

The DR9Q catalog includes fainter objects than in SDSS-I/II, since a fainter limiting magnitude in the target selection was adopted to obtain a high quasar surface density as needed when available (see Pâris et al. 2012 for details). This has the advantage in extending the luminosity coverage when combining DR9 quasars with SDSS-I/II quasars. In this work, we investigate the evolution of the CF by utilizing a large number of quasars at z ≥ 2 in the DR9Q catalog and the extended luminosity coverage of low-redshift quasars from the combination of the DR9Q and the DR7 quasar catalogs.

The SDSS DR7 quasar (DR7Q) catalog consists of 105,783 spectroscopically-confirmed quasars with luminosities brighter than M_i = −22.0, with at least one emission line having a FWHM larger than 1000 km s⁻¹. The objects in this catalog furthermore have highly reliable redshifts. The sky coverage of the sample is about 9380 deg² and the redshifts range from 0.065 to 5.46. The five-band (u, g, r, i, z) magnitudes have typical errors of about 0.03 mag. The spectra cover the wavelength range from 3800 Å to 9200 Å with a resolution of z~2000 (see Schneider et al. 2010 for details).

To study the distribution of the CF for statistical samples of high-z and low-z quasars, we make use of the WISE all-sky data release (Wright et al. 2010) and near-IR observations from the UKIRT Infrared Deep Sky Survey (UKIDSS; Lawrence et al. 2007), in combination with optical photometry/spectroscopy from the SDSS and Galaxy Evolution Explorer (GALEX) surveys (Martin et al. 2005). The WISE all-sky data release consists of imaging of the entire sky in four near-to mid-IR bands centered at 3.4, 4.6, 12 and 22 μm to a depth of 0.04, 0.06, 0.5 and 3.2 mJy (3σ) with an angular resolution of 6′, 6′, 6′, 6′, and 12′, respectively (Wright et al. 2010). UKIDSS is a large-scale near-IR survey covering 7500 deg² of the Northern sky in four near-IR bands (Y, J, H, and K) using the UKIRT Wide Field Camera (Casali et al. 2007). The project is comprised of five surveys in the Large Area Survey, the Galactic Clusters Survey, and the Galactic Plane Survey to a depth of K ~ 18, the Deep Extragalactic Survey to K ~ 21, and the Ultra Deep Survey to K ~ 23. The GALEX space has performed an all-sky imaging survey (AIS) simultaneously in both the far-UV (FUV) and near-UV (NUV) bands with effective wavelengths of 1530 and 2310 Å, respectively, sensitive to m_{AB} ~ 21 in the AIS, and to m_{AB} ~ 25 in the Deep Imaging Survey.

2.2. Quasars at 2.0 ≤ z ≤ 2.4

We assembled a quasar sample at z ~ 2.2 by collecting DR9 quasars in the redshift range 2.0 ≤ z ≤ 2.4. This redshift range is selected to cover the peak of the redshift distribution of DR9Q (z ~ 2.2) (see Figure 22 in Pâris et al. 2012). We thus have a statistically large sample. Moreover, the narrow redshift coverage enables us to de-couple luminosity and redshift effects. For our chosen redshift range, the four WISE wavebands cover ~1–7 μm in the quasar rest frame. Although the data do not cover 10 μm—the position of a bump in the quasar SED due to silicate-dust emission (Hao et al. 2007; Mor & Netzer 2012)—the data do include the SED peak at shorter wavelengths ≤5 μm (Leipski et al. 2010; Mor & Netzer 2012). According to the mean quasar SED in Richards et al. (2006), the IR luminosity at over 1–7 μm is about half of the total IR luminosity at over 1–100 μm (L_{1–100 μm} = 2.03 L_{1–7 μm}). In this work, the IR emission of the dusty torus is measured over 1–7 μm (see Section 3.1).

The WISE photometry is given in the DR9Q catalog by cross-correlating with the WISE All-Sky Data Release using a matching radius of 2.0 arcsec (Pâris et al. 2012). There are 25,607 quasars at 2.0 ≤ z ≤ 2.4 in the DR9Q catalog. To estimate the IR luminosity, we require detections in all four WISE wavebands, resulting in 7971 quasars. Further matching with all five surveys in the UKIDSS data release eight (DR8) with a search radius of 2 arcsec yields a sample of 2056 quasars with detections in all four bands of UKIDSS (Y, J, H, and K). This sample is hereafter called high-z quasars.

2.3. Quasars at 0.7 ≤ z ≤ 1.1

In addition to the peak at z ~ 2.2, there are two peaks in the redshift distribution of the DR9Q catalog at z ~ 0.8 and z ~ 1.6. These peaks are due to known degeneracies in SDSS color space (Pâris et al. 2012). To explore the quasar properties at a redshift distinctive from that of the high-z quasars, the low redshift range was selected as 0.7 ≤ z ≤ 1.1. This redshift region covers the peak at z ~ 0.8 for the DR9Q quasars and there are also numerous quasars from the DR7Q catalog in this range. Therefore, quasar properties can be studied in a wider luminosity range by combining the DR7Q quasars and fainter objects in the DR9Q catalog.

The quasars at 0.7 ≤ z ≤ 1.1 were first selected from the DR9Q catalog. There are 10,392 quasars at 0.7 ≤ z ≤ 1.1 in the DR9Q catalog. 6759 of which have detections in all four WISE bands within a 2 arcsec match radius to the all-sky data release. The further requirement of detections in all the UKIDSS bands within a 2 arcsec match radius reduces the source number to 1574. To produce a similar rest frame wavelength coverage in the ultraviolet as the high-z quasars, we require GALEX NUV and FUV photometry by cross-correlating the SDSS with the GALEX general release 6 and 7 (GR6/GR7) within 3 arcsec. This radius is recommended for matches between GALEX and ground-based optical catalogs (Budavári & Szalay 2008), and it has been used in various works (e.g., Chen et al. 2009; Bianchi et al. 2011; Gezari et al. 2013). The matches with GALEX give 851 quasars with both NUV and FUV detections. These quasars were complemented with quasars at 0.7 ≤ z ≤ 1.1 in the DR7Q catalog (Schneider et al. 2010). There are 16,695 quasars at 0.7 ≤ z ≤ 1.1 in the DR7Q catalog. Matching with the UKIDSS DR8 within 2 arcsec gives 4137 quasars, and further searching WISE within 2 arcsec yields 4093 sources. The requirement of GALEX data within 3 arcsec finalizes a sample of 3125 quasars. After excluding 36 quasars already identified in the DR9Q catalog, the DR7 low-z sample contains 3089 quasars. The combined low-z sample thus consists of 3940 quasars in total.

3. RESULTS

3.1. IR and Bolometric Luminosity

The SED of each quasar was constructed with the available multi-wavelength data as discussed in the previous section (i.e., data from WISE, UKIDSS, SDSS, and GALEX). The near-IR UKIDSS, SDSS, and GALEX data were first corrected for Galactic extinction using the reddening map of Schlegel et al.
Figure 1. Examples of quasar SEDs. From top to bottom: DR9 high-z quasar SDSS J000027.01+030715.5 (z = 2.345); DR9 high-z quasar SDSS J001600.60−003859.2 (z = 2.199), as a red quasar detected in FIRST; DR7 low-z quasar SDSS J004505.67+002528.1 (z = 1.006); DR7 low-z quasar SDSS J020912.02+004719.0 (z = 0.787), as a red quasar. In each panel, the dotted, dashed, and dot-dashed lines denote the positions of 1100 Å, 1 μm, and 7 μm, respectively.

(1998) and the extinction law of Cardelli et al. (1989). These data, together with the WISE data, were directly converted to the rest luminosity at the rest frequency. The SED examples are shown in Figure 1, where it can be seen that the GALEX data were added in the low-z quasars to have the same wavelength coverage as the high-z sources in the UV region.

IR emission is thought to result from optical-UV photons reprocessed by the surrounding torus dust. For our samples, the IR luminosity is integrated in the rest frame wavelength region covered by WISE and UKIDSS. To produce a uniform wavelength coverage, the long-wavelength end is set to 7 μm, which approximately corresponds to the observed WISE band at 22 μm at highest redshift z = 2.4. The short-wavelength limit is set at 1 μm, which separates the accretion disk emission from the torus emission in composite AGN SEDs (e.g., Elvis et al. 1994). The luminosity at 7 μm was estimated by a power-law interpolation or extrapolation with WISE 12 and 22 μm data for both the high-z and low-z quasars. In contrast, the luminosity at 1 μm was calculated by extrapolation with WISE 3.4 and 4.6 μm, WISE 3.4 μm and UKIDSS K data, for the high-z and low-z quasars, respectively. The IR luminosity LIR was then integrated between 1 μm and 7 μm by directly linking the luminosity at 1 μm and 7 μm and the observed data points with a power law in each two adjacent data points. Although the estimated IR luminosity does not extend much into mid-IR, it contains a significant portion of the overall torus emission, as indicated by the short-wavelength peak in the intrinsic AGN SED of Mor & Netzer (2012).

Similar to the IR luminosity, the bolometric luminosity for our sample is integrated over the optical-UV wavelength region covered by all quasars. The blue end of the quasar spectra at z > 2.2 is subject to absorption by the IGM, since the detection of the characteristic scale imprinted by BAOs at z ∼ 2.5 relies on the observed Lyα forest (Pâris et al. 2012; Dawson et al. 2013). Based on the composite spectrum of DR9 quasars, we select 1100 Å as the short-wavelength limit, above which quasar spectra are severely contaminated by the Lyα forest (Pâris et al. 2012). The luminosity at 1100 Å is interpolated or extrapolated from the SDSS u and g data for the high-z quasars, while the same quantity is calculated from interpolation with GALEX NUV and FUV data for the low-z objects. The luminosity over 1100 Å–1 μm was then integrated between 1100 Å and 1 μm by directly linking the luminosity at 1 μm and 1100 Å and the observed data points with a power law in each two adjacent data points. In this work, we call the power-law integrated luminosity over 1100 Å–1 μm the bolometric luminosity, which can be transformed to a real bolometric luminosity over 1 μm–10 keV by multiplying by a factor of ∼1.62 deduced from the mean quasar SED of Richards et al. (2006).

3.2. SED Shape

We investigated the shape of the optical-UV SED by fitting the data points between 1 μm and 1100 Å with a power law, from which the spectral index was obtained. The distribution of spectral index is shown in Figure 2 for both the high-z and
low-\(z\) quasars. We found that low-\(z\) quasars appear slightly bluer than high-\(z\) sources, with median spectral indices of \(-0.33\), and \(-0.48\), respectively. It can also be seen that the spectral index distributions are clearly asymmetric, with a red rail in both populations. In this work, we tentatively define a red quasar as having \(\alpha < 0\), corresponding to a declining SED over 1100 Å–1 \(\mu\)m. We found that 234 high-\(z\) and 159 low-\(z\) quasars are red quasars (see examples in Figure 1); these objects are likely intrinsically red quasars or quasars reddened due to extinction (e.g., Richards et al. 2003).

Interestingly, the bluest SED has a spectral index of 0.29, which is close to the \(\alpha = 1/3\) prediction of the standard thin disk (Shakura & Sunyaev 1973). We found that four high-\(z\) and six low-\(z\) quasars have spectral indices \(\alpha > 0.2\). All of these sources can likely be explained with the standard thin disk.

### 3.3. Analysis on the Covering Factor

The relationship between the IR luminosity and the bolometric luminosity is shown in Figure 3. It is clearly seen that the luminosity of low-\(z\) quasars spans about 1.5 orders of magnitude, with DR9 sources extending to the low luminosity region, as expected from their faintness (Pâris et al. 2012), while the luminosity of high-\(z\) sources covers about one order of magnitude. Significant correlations are found between IR and bolometric luminosity; the Spearman correlation coefficients are \(r_{\text{IR}} = 0.732\) and \(r_{\text{bol}} = 0.893\), both at \(\gg 99.99\%\) confidence levels for the high-\(z\) and low-\(z\) quasars, respectively. However, they follow different dependences. The linear fit gives

\[
\log L_{\text{IR}} = (0.58 \pm 0.01) \log L_{\text{bol}} + (19.13 \pm 0.48)
\]

for the high-\(z\) quasars. For only the DR9 low-\(z\) quasars, the relation becomes

\[
\log L_{\text{IR}} = (0.79 \pm 0.02) \log L_{\text{bol}} + (9.50 \pm 0.70).
\]

In contrast, it is

\[
\log L_{\text{IR}} = (0.81 \pm 0.01) \log L_{\text{bol}} + (8.29 \pm 0.29) \quad (3)
\]

for all the low-\(z\) sources.

We here define the CF as the ratio of the IR to the bolometric luminosity. Significant anti-correlations are found between the CF and the bolometric luminosity with Spearman correlation coefficients of \(r_{\text{bol}} = -0.690\) and \(r_{\text{IR}} = -0.431\), both at \(\gg 99.99\%\) confidence levels for the high-\(z\) and low-\(z\) quasars, respectively (see Figure 3). The linear fit yields

\[
\log L_{\text{IR}}/L_{\text{bol}} = (-0.42 \pm 0.01) \log L_{\text{bol}} + (19.29 \pm 0.48) \quad (4)
\]

for the high-\(z\) quasars. For only the DR9 low-\(z\) quasars, the relation becomes

\[
\log L_{\text{IR}}/L_{\text{bol}} = (-0.22 \pm 0.02) \log L_{\text{bol}} + (9.98 \pm 0.70). \quad (5)
\]

In contrast, it is

\[
\log L_{\text{IR}}/L_{\text{bol}} = (-0.19 \pm 0.01) \log L_{\text{bol}} + (8.53 \pm 0.29) \quad (6)
\]

for all the low-\(z\) sources, which is marginally in agreement with the relation of Ma & Wang (2013) in a similar redshift range. Although the CF follows different dependences on bolometric luminosity, most of the quasars in both populations have similar CF ranges of \(10^{-0.5}–10^{0.2}\).

We collected black hole masses for DR7 low-\(z\) quasars from Shen et al. (2011). In addition, we calculated the black hole masses of DR9 quasars using the same empirical relation as was done for the DR7 low-\(z\) quasars in Shen et al. (2011). These authors utilized the luminosity at 3000 Å and the FWHM of Mg II. For our DR9 quasars, the luminosity at 3000 Å was obtained from interpolation between two adjacent data points, and the FWHM of the Mg II lines was tentatively adopted.
Figure 3. Top: IR luminosity vs. bolometric luminosity; bottom: the covering factor vs. the bolometric luminosity. The black dots are the high-$z$ DR9 quasars, and the red and blue dots are the DR9 and DR7 low-$z$ quasars, respectively. The black line is the linear fit to the high-$z$ quasars and the green line is the fit to all the low-$z$ sources.

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

Figure 4. Left: CF vs. black hole mass; right: CF vs. the Eddington ratio $1.62 \frac{L_{\text{bol}}}{L_{\text{Edd}}}$, in which $1.62 \frac{L_{\text{bol}}}{L_{\text{Edd}}}$ is the bolometric luminosity over $1 \mu m$–10 keV (see text for details). The symbols are the same as in Figure 3.

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

as the sum of the blue and red half width at half maximum (HWHM) provided in the DR9Q catalog (Pâris et al. 2012). In Figure 4, we investigate the relationship between the CF and black hole mass and the CF and the Eddington ratio. The Eddington ratio is estimated as $1.62 \frac{L_{\text{bol}}}{L_{\text{Edd}}}$, in which $1.62 \frac{L_{\text{bol}}}{L_{\text{Edd}}}$ is the real bolometric luminosity over $1 \mu m$–10 keV calculated from the 1100 Å–1 $\mu m$ bolometric luminosity with a correction deduced from the mean quasar SED of Richards et al. (2006). $L_{\text{Edd}}$ is the Eddington luminosity. There are significant anti-correlations between the CF and black hole mass with $L_{\text{bol}}$.
Figure 5. Distribution of the CF in the bolometric luminosity range $10^{45.8} - 10^{46.2}$ erg s$^{-1}$. The solid line is for the high-$z$ quasars, while the dashed line is for low-$z$ sources.

Spearman correlation coefficients of $-0.209$ and $-0.294$ at confidence levels $\gg 99.99\%$ for the low-$z$ and high-$z$ quasars, respectively. However, there is no strong correlation when the two populations are combined. While there is a strong anticorrelation between the CF and Eddington ratio with a Spearman correlation coefficient of $-0.217$ at a confidence level $\gg 99.99\%$ in the high-$z$ quasars, there are no strong correlations for either the low-$z$ quasars or the combined quasars. In the case of the low-$z$ quasars, our results are in agreement with those of Ma & Wang (2013) and those of Cao (2005) for Palomar-Green quasars.

3.4. Evolution of the Covering Factor

In flux-limited surveys, quasars at high redshifts systematically have higher luminosities than objects at low redshifts, as can be clearly seen in Figure 3. Moreover, significant anticorrelations are apparently present between the CF and bolometric luminosity for both the high-$z$ and low-$z$ quasars. To avoid the coupled effects of luminosity and redshift, we select an overlapping bolometric luminosity range of $\log L_{\text{bol}} = 45.8 - 46.2$ erg s$^{-1}$ to study the difference in the CF between the high-$z$ and low-$z$ quasars. The distributions of CF are displayed in Figure 5 for 778 low-$z$ and 966 high-$z$ quasars in that luminosity range. We found that the CFs of high-$z$ quasars are systematically higher than those of the low-$z$ quasars, with a median log CF value of $-0.32$ and $-0.06$ for the low-$z$ and high-$z$ quasars, respectively. The Kolmogorov–Smirnov statistic (KS) test shows a significant difference between the CF distributions of the high-$z$ and low-$z$ quasars: a KS statistic value of 0.696 and a probability of $P \ll 10^{-4}$ that the considered samples are drawn from the same distribution. The CF difference between the high-$z$ and low-$z$ quasars strongly implies an evolution in the CF from high to low redshifts.

In Figure 6, we show the relationship between the CF and black hole mass and the CF and the Eddington ratio in the overlapping luminosity range. Apparently, high-$z$ sources have higher CFs; however, they are indistinguishable from low-$z$ sources in their distributions of black hole mass and Eddington ratio. Both populations are in the range of $10^8 - 10^{10} M_\odot$ and 0.01–1.0 for black hole mass and Eddington ratio, respectively. This indicates that the CF difference between the high-$z$ and low-$z$ quasars may not be caused by the dependence of the CF on black hole mass and/or Eddington ratio.

4. DISCUSSION

As jet emission is usually powerful in radio-loud quasars, it could more or less contribute in both the IR and optical/UV bands. Especially in blazars, the contribution from jet emission is significant, and usually dominates over thermal emission from the accretion disk and torus, as the relativistic jets of blazars are beamed toward us. In this case, the IR and optical-UV luminosities hardly indicate the torus reprocessed emission or the accretion disk emission. Using these luminosities thus results in inappropriate CF measurements. We checked the radio counterparts of our samples in the Faint Images of the Radio Sky at Twenty centimeters (FIRST) 1.4 GHz radio catalog (Becker et al. 1995). We found that 79 high-$z$ and 258 low-$z$ quasars are detected in FIRST, resulting in a total of 337 objects out of 5996 quasars. As an example, the SED of the FIRST-detected high-$z$ quasar SDSS J001600.60$-$003859.2 ($z = 2.199$) is shown in Figure 1. The SED declines from the IR to the UV bands, implying that the synchrotron jet emission may likely dominate this source, as is true in typical blazars (see Figure 10 in Donato et al. 2001). However, such a red SED has also been found in non-FIRST-detected quasars, as shown in Figure 1 for the DR7 low-$z$ quasar SDSS J020912.02+004719.0 ($z = 0.787$). This object could be a red or reddened quasar, as previously found.
We revisited the results by only including those low-
WISE bolometric luminosities of detections are expected to follow the relation of the IR and the former being systematically brighter than the latter. Together with the significant correlation between the WISE flux and the SDSS $r$ flux in WISE-detected objects, quasars without WISE detections are expected to follow the relation of the IR and bolometric luminosities of WISE-detected high-$z$ quasars (see Figure 3).

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Figure 3. We revisited the results by only including those low-
WISE-detected high-$z$ quasars with a WISE flux density above the WISE flux limit after being redshifted to $z = 2.2$. The CF difference between the high-$z$ and low-$z$ quasars is still significant at overlapping bolometric luminosities. Moreover, we found the same result in terms of quasars in the overlapping IR luminosity region $10^{45.6} - 10^{46.0} \text{ erg s}^{-1}$. All these analyses show that our results are not likely caused by the non-inclusion of the IR-faint, high-$z$ quasars.

Quasars usually have strong, broad emission lines, which could affect the photometry when emission lines are redshifted into certain wavebands. In principle, the line contribution to the fluxes at relevant wavebands could be subtracted considering the corresponding spectra and the method proposed by Elvis et al. (2012). In this work, we prefer not to remove any line contribution, since we mainly focus on the systematic difference between the high-$z$ and low-$z$ quasars. However, analyses have been performed to investigate the influence of line contributions on our results. We only considered the three strongest emission lines, Ly$\alpha$, H$\alpha$, and H$\beta$, and found that they are indeed covered by various wavebands in our considered redshift range. While the Ly$\alpha$ line is redshifted into the NUV bandwidth for low-$z$ quasars, H$\alpha$ is moved into the $J$ band for low-$z$ quasars and into the $K$ band for high-$z$ objects. H$\beta$ falls in the SDSS $z$ band for low-$z$ quasars and into the $H$ band for high-$z$ sources. As stated in Elvis et al. (2012), the correction for line contribution is dependent on the line equivalent width (EW) and the bandwidth (see Equation (1) in Elvis et al. 2012). For the typical line EW and the bandwidths of the related wavebands, we found that the corrections are about 0.1 dex for H$\alpha$ and 0.02 dex for H$\beta$ in both the low-$z$ and high-$z$ sources. The corrections are about 0.04 dex for Ly$\alpha$ only in the low-$z$ quasars. While there are overestimations on the bolometric luminosity in both the high-$z$ and low-$z$ quasar samples due to the inclusion of line contributions from H$\alpha$ and H$\beta$, the low-$z$ sources would have additional overestimates of about 0.04 dex from Ly$\alpha$. However, this factor certainly is not enough to explain the systematic CF difference between the high-$z$ and low-$z$ quasars in the overlapping bolometric luminosity range. Although the contribution of H$\alpha$ is non-trivial, it does not affect our result since we found similar results after excluding the relevant wavebands including the H$\alpha$ line. Moreover, we checked the results using the bolometric luminosity estimated from the

in SDSS (Richards et al. 2003). We grouped the SEDs of all FIRST-detected quasars together by normalizing the luminosity at 1 $\mu$m, and found that their group SED is similar to that of non-FIRST-detected sources with a prominent Big Blue Bump. The similar distribution of the spectral index over 1100 Å–1 $\mu$m in the two populations further supports their SED similarities. As stated in Richards et al. (2006) and Shang et al. (2011), the mean SEDs of radio-quiet and radio-loud quasars in the NUV and IR are quite similar. Therefore, we expect that the FIRST-detected quasars will not affect our statistical results, due to both their small source fraction ($\sim$5.6%) and their similar SEDs to non FIRST objects.

At different redshifts, the observed data at same wavebands actually sample different rest frequencies. The bias caused by SED sampling may not be severe in the optical-UV region. However, there is likely SED undersampling in the IR due to the sparse WISE data. To check the bias caused by the IR data sampling, we calculated the 1–7 $\mu$m IR luminosity from the mean quasar SED of Richards et al. (2006) for $z = 2.2$ and $z = 0.9$ using the same power-law integration method on WISE data as was used for our samples. While the mean SED gives an IR luminosity of $10^{45.65} \text{ erg s}^{-1}$, the values are $10^{45.57} \text{ erg s}^{-1}$ and $10^{45.63} \text{ erg s}^{-1}$ for the samples at high and low redshifts, respectively. While the underestimation due to the sparse WISE data is not significant, the IR luminosities of the low-$z$ quasars are basically higher than those of the high-$z$ quasars, albeit only slightly. Therefore, if one takes the IR data sampling into account, the difference in the CF between the high-$z$ and low-$z$ quasars can be even larger.

In this work, we required detections in all four WISE wavebands to calculate the IR luminosity. Therefore, due to the shallow WISE sensitivity, especially at 22 $\mu$m, we might have missed a lot of IR-faint, high-$z$ quasars, although they were detected in SDSS. We found that the distribution of SDSS $r$ magnitudes of the high-$z$ quasars detected in all four WISE bands is significantly different from that of the WISE non-detections, with the former being systematically brighter than the latter. Together with the significant correlation between the WISE flux and the SDSS $r$ flux in WISE-detected objects, quasars without WISE detections are expected to follow the relation of the IR and bolometric luminosities of WISE-detected high-$z$ quasars (see Figure 3). We revisited the results by only including those low-$z$ quasars with a WISE flux density above the WISE flux limit after being redshifted to $z = 2.2$. The CF difference between the high-$z$ and low-$z$ quasars is still significant at overlapping bolometric luminosities. Moreover, we found the same result in terms of quasars in the overlapping IR luminosity region $10^{45.6} - 10^{46.0} \text{ erg s}^{-1}$. All these analyses show that our results are not likely caused by the non-inclusion of the IR-faint, high-$z$ quasars.
luminosity at 3000 Å, which is interpolated from two adjacent data points and is not affected by line contributions. We found a similar result, i.e., a significant CF difference between the high-$z$ and low-$z$ quasars. In conclusion, line contaminations do not affect our results, although we did not perform the corrections.

While the black hole masses of DR7 low-$z$ quasars were collected from Shen et al. (2011), those of the DR9 quasars were obtained by tentatively using the FWHM of Mg ii lines as the sum of the blue and red HWHMs provided in the DR9Q catalog (Pâris et al. 2012). Thus, the black hole masses of the DR9 quasars are only illustrative, not conclusive. It is still ambiguous whether it is necessary to subtract a narrow line component for Mg ii, as some works do so (e.g., McLure & Dunlop 2004) while others do not (e.g., Vestergaard & Osmer 2009). The comparison of the FWHM of entire Mg ii line with the FWHM of the broad Mg ii line for the DR7 quasars in Shen et al. (2011) shows that the majority of sources ($\sim$67%) have a difference within 0.02 dex, corresponding to 0.04 dex in the black hole mass estimations. Therefore, our black hole masses for the DR9 quasars might be reasonable, although not strict. In Figure 4, the black hole masses of the DR9 quasars are reasonably in the range of $10^{7} - 10^{9}$ M$_{\odot}$, with the high-$z$ sources having systematically larger values perhaps simply due to their larger luminosities relative to low-$z$ sources. Contrary to no correlation in the low-$z$ quasars, there is a strong anti-correlation between the CF and the Eddington ratio in the high-$z$ objects. It is unclear why the high-$z$ quasars are different from their low-$z$ counterparts. It is worth noting that the high-$z$ sample size is relatively small, and/or the uncertainty in the black hole mass estimate is not quantitatively well evaluated. The larger sample from the next version of BOSS and the future extended BOSS (eBOSS) will help to study these effects.

The quasars in the DR7Q catalog were selected as sources with at least one emission line having a FWHM larger than 1000 km s$^{-1}$, while the DR9 quasars were selected as either displaying at least one emission line with an FWHM larger than 500 km s$^{-1}$ or, if not, having an interesting/complex set of absorption features. Due to different selection criteria, the high-$z$ quasars in the DR9Q catalog may likely be biased toward Type 2 quasars, as they may include a fraction of sources with narrower emission lines than typical Type 1 quasars. Since Type 2 AGNs are thought to have larger CFs than Type 1 AGNs (e.g., Elitzur 2012), this selection bias perhaps will at least partly produce the higher CFs seen in the high-$z$ quasars compared to the low-$z$ quasars, which are mainly from the DR7Q catalog. However, we found that almost all quasars at $2 < z < 2.4$ in the DR9Q catalog (~99%) have FWHM $> 1000$ km s$^{-1}$ in at least one of the Mg ii or C iv lines. In fact, in our high-$z$ quasar sample, 2048 of 2056 quasars (~99.6%) have FWHM $> 1000$ km s$^{-1}$ and there are 962 out of a total of 966 high-$z$ quasars (~99.6%) having FWHM $> 1000$ km s$^{-1}$ in the overlapping bolometric luminosity range. When we restrict FWHM $> 2000$ km s$^{-1}$ in 960 of 966 quasars, we found the same log CF median value of $-0.06$, proving the significant CF difference between these broad line high-$z$ quasars and low-$z$ quasars. We further checked the results by only including quasars with a narrow range of spectral indices in the overlapping bolometric luminosity range. In the range of $-0.3 < \alpha < -0.2$, we found that the CF difference remained significant with median log CF values of $-0.11$, and $-0.32$ for the high-$z$ and low-$z$ quasars, respectively. The KS test shows a significant difference between the high-$z$ and low-$z$ quasars in their CF distributions, while there is no strong difference in the $\alpha$ distributions. Similar results are found in other $\alpha$ ranges. Finally, we checked the results by comparing the high-$z$ quasars with only the DR9 low-$z$ quasars. The median log CF value is $-0.31$ for the low-$z$ DR9 quasars in the overlapping $L_{\text{bol}}$ range, which confirms the significant difference compared to the high-$z$ quasars. We therefore conclude that the CF difference between the high-$z$ and low-$z$ quasars may less likely be caused by the selection bias in the DR9Q catalog.

For the first time, the large sample of DR9 quasars enables us to explore the statistical properties of the IR luminosity and the CF for quasars at $z > 2$. The uniqueness of our sample is that we selected the sources with detections in the IR through the UV from various surveys. Although the sample size is much reduced, our sample is large enough for statistical investigations. More importantly, the bolometric luminosity can be better constrained with multi-wavelength data compared to estimates from the UV luminosity at a single wavelength (usually 3000 Å) or the integration over a narrow UV wavelength range (Mor & Trakhtenbrot 2011; Calderone et al. 2012; Ma & Wang 2013). Due to the lack of X-ray measurements, we calculated the bolometric luminosity only over 1100 Å–1 μm. This range, however, represents the majority (~62%) of the overall bolometric luminosity over $1\mu$m–10 keV according to the mean quasar SED of Richards et al. (2006). Instead of calculating the torus IR luminosity using certain models (Mor & Trakhtenbrot 2011; Roseboom et al. 2013), we obtained the IR luminosity from direct power-law integrations, using basically the same produce as Calderone et al. (2012) and Ma & Wang (2013). While we have proved that the IR luminosity calculation does not introduce significant systematic biases when comparing the high-$z$ to low-$z$ quasars, the same is certainly also true in each population since the redshift range is rather narrow in each sample. Benefiting from our source selection, the dispersion of the relationship between the IR and bolometric luminosities is much less than that of Ma & Wang (2013) at a similar redshift (see Figure 3), although their IR luminosity is in the $3–10\mu$m range.

We have shown that the anti-correlations between the CF and the bolometric luminosity follow different tracks for high-$z$ and low-$z$ quasars, while their CFs cover a similar range (see Figure 3). The overlapping bolometric luminosity actually corresponds to the high luminosity end of low-$z$ quasars, while it corresponds to the low luminosity end of the high-$z$ quasars. Therefore, it is quite natural to see a higher CF for high-$z$ quasars at overlapping bolometric luminosities. While the anti-correlation between the CF and bolometric luminosity has been found on various occasions and different scenarios have been proposed (e.g., Maiolino et al. 2007; Mor & Trakhtenbrot 2011; Calderone et al. 2012; Ma & Wang 2013), we found a higher CF in high-$z$ quasars, implying an evolution of the CF with redshift. This result is consistent with the findings that the fraction of obscured AGNs increases significantly with redshift in hard-X-ray-selected samples (e.g., La Franca et al. 2005; Hasinger 2008). According to the merger scenario, the merger triggers star formation and quasar activity as well. The quasars finally blow away the surrounding dust and gas and outshine the host galaxy. At that time, plenty of materials supply the central accretion process and the formation of quasar structures. An increase in the CF at high redshift could be naturally expected based on the larger gas content. This increase could be associated with enhanced star formation rates in high-$z$ galaxies, which have also been observed in the host galaxies of high-$z$ AGNs (e.g., Shi et al. 2009; Tacconi et al. 2010).
5. SUMMARY

By constructing SEDs for a sample of 5996 quasars at $2.0 \leq z \leq 2.4$ or $0.7 \leq z \leq 1.1$ from the SDSS DR9Q and DR7Q catalogs, the CF of the dusty torus was estimated as the ratio of the IR luminosity to the bolometric luminosity. We found significant anti-correlations between the CF and bolometric luminosity, both in high-$z$ and low-$z$ quasars. However, these subsamples follow different tracks. At overlapping bolometric luminosities, the CFs of high-$z$ quasars are systematically larger than those of low-$z$ quasars, implying an evolution of the CF with redshift.

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