How Does the Polar Dust Affect the Correlation between Dust Covering Factor and Eddington Ratio in Type 1 Quasars Selected from the Sloan Digital Sky Survey Data Release 16?

Yoshiki Toba

123, Yoshihiro Ueda4, Poshak Gandhi4, Claudio Ricci56, Denis Burgarella7, Veronica Buat7, Tohru Nagao3, Shinkl Oyabu8, Hideo Matsuhara9,10, and Bau-Ching Hsieh2

1 Department of Astronomy, Kyoto University, Kitashirakawa-Ohike-cho, Sakyu-ku, Kyoto 606-8502, Japan
toba@kusastro.kyoto-u.ac.jp
2 Academia Sinica Institute of Astronomy and Astrophysics, 11F of Astronomy-Mathematics Building, AS/NTU, No.1, Section 4, Roosevelt Road, Taipei 10617, Taiwan
3 Research Center for Space and Cosmic Evolution, Ehime University, 2-5 Bunkyo-cho, Matsuyama, Ehime 790-8577, Japan
4 Department of Physics and Astronomy, University of Southampton, Highfield, Southampton SO17 1BJ, UK
5 Núcleo de Astronomía de la Facultad de Ingeniería, Universidad Diego Portales, Av. Ejército Libertador 441, Santiago, Chile
6 Iavi Institute for Astronomy and Astrophysics, Peking University, Beijing 100871, People’s Republic of China
7 Aix Marseille Univ. CNRS, CNES, LAM Marseille, France
8 Institute of Liberal Arts and Sciences, Tokushima University, Minami Joujusnina-Machi 1-1, Tokushima, Tokushima 770-8502, Japan
9 Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 3-1-1 Yoshinodai, Chuo-ku, Sagamihara, Kanagawa 252-5210, Japan
10 Department of Space and Astronautical Science, The Graduate University for Advanced Studies, SOKENDAI, 3-1-1 Yoshinodai,Chuo-ku, Sagamihara, Kanagawa 252-5210, Japan

Received 2020 September 22; revised 2021 January 18; accepted 2021 February 8; published 2021 May 7

Abstract

We revisit the dependence of the covering factor (CF) of dust torus on physical properties of active galactic nuclei (AGNs) by taking into account an AGN polar dust emission. The CF is converted from a ratio of infrared (IR) luminosity contributed from AGN dust torus (L_IR torus) and AGN bolometric luminosity (L_bol), by assuming a nonlinear relation between luminosity ratio and intrinsic CF. We select 37,181 type 1 quasars at z < 0.7 from the Sloan Digital Sky Survey Data Release 16 quasar catalog. Their L_bol, black hole mass (M_BH), and Eddington ratio (λ_Edd) are derived by spectral fitting with XSFit. We conduct spectral energy distribution decomposition by using X-CIGALE with a clumpy torus and polar dust model to estimate L_IR torus without being affected by the contribution of stellar and AGN polar dust to IR emission. For 5752 quasars whose physical quantities are securely determined, we perform a correlation analysis on CF and (i) L_bol, (ii) M_BH, and (iii) λ_Edd. As a result, anticorrelations for CF–L_bol, CF–M_BH, and CF–λ_Edd are confirmed. We find that incorporating the AGN polar dust emission makes those anticorrelations stronger compared to those without considering it. This indicates that polar dust wind probably driven by AGN radiative pressure is one of the key components to regulate obscuring material of AGNs.

Unified Astronomy Thesaurus concepts: Quasars (1319); Supermassive black holes (1663); Catalogs (205)

Supporting material: FITS file

1. Introduction

An obscuring dusty structure surrounding a supermassive black hole (SMBH) plays an important role in the diversity of observational phenomena of active galactic nuclei (AGNs) in the context of a unified model (e.g., Antonucci 1993; Urry & Padovani 1995). The obscuring material that is often called “dust torus” (e.g., Krolik & Begelman 1986) is expected to be compact (<10 pc) and responsible for infrared (IR) emission from AGNs (e.g., Rees et al. 1969; Jaffe et al. 2004; Tristram et al. 2007).

Although it has been believed that dust torus is a key component of the AGNs, many challenges still remain. What is the structure of the circumnuclear dust? What is the main physical mechanism to regulate the obscuring material surrounding AGNs? These have been extensively studied both from the theoretical side (e.g., Wada & Norman 2002; Schartmann et al. 2005; Fritz et al. 2006; Kawakatu & Wada 2008; Nenkov et al. 2008a, 2008b; Wada 2012, 2015; Siebenmorgen et al. 2015; Namekata & Umemura 2016; Stalevski et al. 2016; Tanimoto et al. 2019) and from the observational side (e.g., Suganuma et al. 2006; Ueda et al. 2007; Gandhi et al. 2009, 2015; Alonso-Herrero et al. 2011; Kishimoto et al. 2011; Ramos Almeida et al. 2011; Ricci et al. 2014; Brightman et al. 2015; Imanishi et al. 2016, 2018; Baba et al. 2018; Baloković et al. 2018; Izumi et al. 2018; Hönig 2019; Marchesi et al. 2019; see also Netzer 2015; Ramos Almeida & Ricci 2017; Hickox & Alexander 2018, and references therein).

We focus here on the geometrical covering fraction of dust torus, a fundamental parameter in the AGN unified model. The dust covering factor (CF) is defined as the fraction of the sky, as seen from the AGN center, that is blocked by heavily obscuring dust. The CF also provides important information on the number of obscured AGNs. Many works have reported that the CF may depend on AGN luminosity, wherein CF is often defined as type 2 AGN fraction (e.g., Simpson 2005; Toba et al. 2012, 2013, 2014, 2017), the IR-to-bolometric luminosity (e.g., Maiolino et al. 2007; Gandhi et al. 2009; Gu 2013; Ma & Wang 2013; Roseboom et al. 2013), or X-ray-obscured AGN fraction (e.g., Ueda et al. 2003, 2014; Hasinger 2008; Burlon et al. 2011; Merloni et al. 2014) (but see also, e.g., Dwelly & Page 2006; Lawrence & Elvis 2010; Mateos et al. 2017; Ichikawa et al. 2019, who reported weak or no significant dependence).

The CF may also depend on redshift (e.g., La Franca et al. 2005; Hasinger 2008; Gu 2013; Merloni et al. 2014; Ueda et al. 2014), as well as the counterargument of no significant evolution in at least a certain redshift range (e.g., Toba et al. 2014; Vito et al. 2018).
Recently, Ricci et al. (2017) reported that the key parameter determining the X-ray CF may be the Eddington ratio ($\lambda_{\text{Edd}}$) rather than AGN luminosity (e.g., bolometric luminosity, $L_{\text{bol}}$) based on 731 hard-X-ray-selected AGNs with a median redshift of 0.0367. Ezhiode et al. (2017) performed a correlation analysis for 51 X-ray/optically selected type 1 AGNs at $z < 0.4$, and combining the correlation analysis with simulations, they found that the CF is more strongly anticorrelated with $\lambda_{\text{Edd}}$ than with $L_{\text{bol}}$. Zhuang et al. (2018) also reported that the CF decreases with increasing $\lambda_{\text{Edd}}$ up to $\sim 0.5$ based on 76 Palomar–Green (PG) quasars at $z < 0.5$. Toba et al. (2019a) found that the luminosity ratio of 6 $\mu$m and absorption-corrected hard X-ray luminosity for AGNs (that is expected to be an indicator of CF) depends on $\lambda_{\text{Edd}}$, and that a correlation would be applicable even for a Compton-thick AGN (Toba et al. 2020c).

On the other hand, Cao (2005) reported no correlation between the near-IR (NIR)-to-bolometric luminosity ratio (which is an indicator of CF) and $\lambda_{\text{Edd}}$ for PG quasars, whereas there is a significant correlation between CF–$L_{\text{bol}}$ and CF–central black hole mass ($M_{\text{BH}}$). These trends were also reported by Ma & Wang (2013) based on 17,639 quasars at $0.76 < z < 1.17$ selected from the Sloan Digital Sky Survey (SDSS; York et al. 2000).

The discrepancy in the above works may be partially because of the difference in sample selection, redshift distribution, and the definition of CF. In particular, statistical works on the CF for quasars tend to employ $L_{\text{IR}}/L_{\text{bol}}$ as the CF. However, recent works suggested that $L_{\text{IR}}/L_{\text{bol}}$ may not be always a good indicator of the CF caused by anisotropy in the IR emission of dust torus (e.g., Stalevski et al. 2016; Mateos et al. 2017; Zhuang et al. 2018). Because $L_{\text{IR}}/L_{\text{bol}}$ and the CF are not connected by a simple linear relation, one needs a conversion from the luminosity ratio to the CF (see Section 3.3). In addition, the derived NIR luminosity for the CF may be contaminated by stellar emission, which may not be negligible, especially for less luminous quasars (e.g., Mateos et al. 2015; Toba et al. 2019a). Furthermore, more recently, polar dust wind probably driven by AGN radiative pressure has been shown to be a ubiquitous contributor to the IR emission (e.g., Hönig et al. 2013; Tristram et al. 2014; López-Gonzaga et al. 2016; Leftley et al. 2018; Asmus 2019; Stalevski et al. 2019). Lyu & Rieke (2018) demonstrated that the observed variety of their broadband IR spectral energy distribution (SED) can be explained by considering the polar dust component. As Asmus (2019) pointed out, we may need to take into account the polar dust emission when deriving the CF from $L_{\text{IR}}/L_{\text{bol}}$.

In this work, we revisit the relationship between the CF and $L_{\text{bol}}$, $M_{\text{BH}}$, and $\lambda_{\text{Edd}}$ for type 1 quasars at $z < 0.7$ selected from the SDSS quasar catalog Data Release (DR) 16 (DR16Q; Lyke et al. 2020) that has been recently published. For this enormous number of type 1 quasars, we extract IR emission purely from dust torus after correcting for the stellar and polar dust emission based on the SED fitting with a clumpy torus model and polar dust model, and we convert the luminosity ratio to intrinsic CF following Stalevski et al. (2016). This paper is organized as follows. Section 2 describes the sample selection of type 1 quasars, our SED modeling, and spectral fitting to the SED spectra. In Section 3, we present the results of the SED fitting, spectral fitting, and the dependence of the CF on $L_{\text{bol}}$, $M_{\text{BH}}$, and $\lambda_{\text{Edd}}$. In Section 4, we show a correlation analysis and discuss possible uncertainties of the results and comparison of previous works. We summarize the results of the study in Section 5. Throughout this paper, the adopted cosmology is a flat universe with $H_0 = 70.0$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.30$, and $\Omega_{\Lambda} = 0.70$. Unless otherwise noted, $z$ refers to the spectroscopic redshift, and an initial mass function (IMF) of Chabrier (2003) is assumed.

2. Data and Analysis

2.1. Sample Selection

A flowchart of our sample selection process is shown in Figure 1. In this work, we focus on spectroscopically confirmed type 1 quasars whose $L_{\text{bol}}$, $M_{\text{BH}}$, and $\lambda_{\text{Edd}}$ can be securely estimated. We sampled quasars that were drawn from the DR16Q (v411), which contains 750,414 type 1 quasars up to $z \sim 6.0$.

Aside from the SDSS imaging data, 3.4 and 4.6 $\mu$m data taken from the Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010) and information on source variability from the Palomar Transient Factory (PTF; Law et al. 2009; Rau et al. 2009) were used for target selection of quasars (see Sections 2.1 and 2.2 in Lyke et al. 2020, for more details). The targeted objects were automatically classified as QSO, STAR, or GALAXY based on the SDSS spectra. In addition, objects that were initially classified as QSO at $z_{\text{pipe}} > 3.5$ by the SDSS pipeline were reclassified for visual inspection (see Section 3.2 in Lyke et al. 2020).

Figure 1. Flowchart of the process to the quasar sample for a correlation analysis.
Compared to previous SDSS quasar catalogs (e.g., DR7Q, Schneider et al. 2010; DR9Q, Pâris et al. 2012; DR14Q, Pâris et al. 2018), DR16Q extends coverage of luminosity to much less luminous quasars given a redshift (see Figures 7 in Pâris et al. 2018 and Lyke et al. 2020). Hence, our quasar sample is expected to cover a wide range of $L_{bol}$, $M_{BH}$, and $\lambda_{edd}$ compared with those derived from previous SDSS quasar catalogs employed in previous works on CF (e.g., Gu 2013; Ma & Wang 2013; Roseboom et al. 2013).

We first narrowed down the sample to objects with \textsc{ZWARNING}=0, which ensures a confident spectroscopic classification and redshift measurement for quasars (Bolton et al. 2012). We then extracted objects with $0 < z < 0.7$ because we aim to estimate $M_{BH}$ based on a recipe using H/β (see Section 2.4) that is detectable for objects at $z$ up to ~0.7 given a spectral coverage of the SDSS spectrograph. Note that it is possible to measure $M_{BH}$ for objects at $z > 0.7$ based on recipes using other emission lines (such as CIV and MgII). However, to avoid being affected by possible systematic uncertainties of $M_{BH}$ because of using different recipes, we adopted the same recipe for all quasars and performed a correlation analysis (see Sections 2.4 and 4.1). Eventually, 37,181 quasars were selected as a sample. We note that the size of the quasar sample at $z < 0.7$ selected from the DR16Q is significantly increased by ~15,000 from DR14Q.

2.2. Photometric Data

For those 37,181 quasars, we compiled optical to mid-IR (MIR) photometry, most of which are already available in DR16Q. In addition to SDSS optical data ($u, g, r, i,$ and $z$) corrected for Galactic extinction (Schlafly & Finkbeiner 2011), we utilized the IR data taken with the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006), the UKIRT Infrared Deep Sky Survey (UKIDSS; Lawrence et al. 2007), and WISE (see Section 7 in Lyke et al. 2020 for a complete description of the above data).

Note that DR16Q newly employed unWISE (Lang 2014) instead of the ALLWISE catalog (Cutri et al. 2014). unWISE provides deep 3.4 and 4.6 $\mu$m data that are force-photometered at the locations of SDSS sources (Lang et al. 2016). On the other hand, WISE 12 and 22 $\mu$m data are still quite useful for this work because those wavelengths are expected to trace the emission from the dusty torus (e.g., Toba et al. 2014). Hence, we compiled those MIR data from ALLWISE with a search radius of 2″ in the same manner as Pâris et al. (2018).

Consequently, we have at maximum 13 photometric data ($u, g, r, i, z, Y, J, H, K, K_s, 3.4, 4.6, 12,$ and 22 $\mu$m) for the SED fitting (see Section 2.3). Among 37,181 quasars, 3345 (9.0%), 5515 (14.8%), 34,683 (93.3%), and 37,155 (99.9%) objects are detected by 2MASS, UKIDSS, ALLWISE, and unWISE, respectively. We used profile-fit photometry for 2MASS-detected sources with $rd_{flg} = 1^{12}$ and that for WISE 12 and/or 22 $\mu$m detected sources with $cc_{flag} = 0^{13}$ (which ensures clean photometry without being affected by possible artifacts) at each band. If an object lies outside the UKIDSS footprint, its NIR flux densities are taken from 2MASS (if that object is detected). Otherwise, we always refer to the UKIDSS as NIR data.

### Table 1

| Parameter                        | Value |
|----------------------------------|-------|
| $\tau_{\text{min}}$ (Gyr)        | 1.0, 5.0 |
| age (Gyr)                        | 5.0 |
| SSP (Bruzual & Charlot 2003)     |       |
| IMF                              | Chabrier 2003 |
| Metallicity                      | 0.02 |
| Dust Attenuation (Charlot & Fall 2000) | |
| $A_{\text{SM}}$                  | 0.01, 0.01, 0.2, 0.3, 0.4, 0.6, 0.8, 1.0 |
| slope$_{\text{ISM}}$             | -0.7 |
| slope$_{\text{BC}}$              | -1.3 |
| AGN Disk + Torus Emission (Stalevski et al. 2016) | |
| $\tau_{\text{0}}$                | 3.5, 9 |
| $p$                              | 0.0, 1.0, 1.5 |
| $q$                              | 0.0, 1.0, 1.5 |
| $\Delta$ (deg)                   | 10, 30, 50 |
| $R_{\text{max}} / R_{\text{min}}$ | 30 |
| $\theta$ (°)                     | 0 |
| $f_{\text{AGN}}$                 | 0.5, 0.6, 0.7, 0.8, 0.9, 0.99 |
| AGN Polar Dust Emission (Yang et al. 2020) | |
| extinction low                   | SMC |
| $E(B-V)$                         | 0.0, 0.05, 0.1, 0.15, 0.2, 0.3, 0.4 |
| $T_{\text{max}}$ (K)             | 100.0, 500.0, 1000.0 |
| Emissivity $\beta$               | 1.6 |

### Table 2

2.3. Broadband SED Fitting with X-CIGALE

To derive IR luminosity contributed only from AGN dust torus ($L_{\text{IR}}$), we conducted the SED fitting by considering the energy balance between the UV/optical and IR. We employed a new version of Code Investigating GALaxy Emission (CIGALE; Burgarella et al. 2005; Noll et al. 2009; Boquien et al. 2019), so-called X-CIGALE$^{14}$ (Yang et al. 2020). This code enables us to handle many parameters, such as star formation history (SFH), single stellar population (SSP), attenuation law, AGN emission, dust emission, and radio synchrotron emission (see, e.g., Boquien et al. 2014, 2016; Buat et al. 2014, 2015; Ciesla et al. 2017; Lo Faro et al. 2017; Toba et al. 2019b; Burgarella et al. 2020). Aside from an implementation of the SED fitting even for X-ray data, X-CIGALE incorporates a clumpy two-phase torus model (SKIRTOR$^{15}$; Stalevski et al. 2012, 2016) and a polar dust emission as AGN templates. According to Yang et al. (2020), we consider the dust responsible for type 1 AGN obscuration as polar dust (i.e., the polar dust provides obscuration for the nucleus and the additional IR emission from the absorbed energy; see Figure 4 in Yang et al. 2020 for a schematic view of polar dust). Parameter ranges used in the SED fitting are tabulated in Table 1.

We adopted a delayed SFH model, assuming a single starburst with an exponential decay (e.g., Ciesla et al. 2015, 2016), where we fixed the age of the main stellar population in the galaxy to be the same as what we used for the

---

12 https://irsa.ipac.caltech.edu/data/2MASS/docs/releases/first/doc/sec4_4.html
13 http://wise2.ipac.caltech.edu/docs/release/allsky/expsup/sec4_4g.html
14 https://gitlab.lam.fr/gyang/cigale/tree/ray
15 https://sites.google.com/site/skirtorus
galaxy template when fitting to the SDSS spectra (see Section 2.4). We parameterized the e-folding time of the main stellar population ($t_{\text{main}}$). The influence of fixing the age of the main stellar population on the CF is discussed in Section 4.3.

We chose the SSP model (Bruzual & Charlot 2003), assuming the IMF of Chabrier (2003), and the standard nebular emission model included in X-CIGALE (see Inoue 2011).

For attenuation of dust associated with the host galaxy, we utilized a model provided by Charlot & Fall (2000) that has two different power-law attenuation curves: the power-law slope of the attenuation in the interstellar medium (ISM), and birth clouds (BC) that were fixed in this work. We parameterized the V-band attenuation in the ISM ($A_V^{\text{ISM}}$).

AGN emission from the accretion disk and dust torus was modeled by using SKIRT, a clumpy two-phase torus model produced in the framework of the 3D radiative transfer code, SKIRT (Baes et al. 2011; Camps & Baes 2015). This torus model consists of seven parameters: torus optical depth at 9.7 μm ($\tau_{9.7}$), torus density radial parameter (p), torus density angular parameter (q), angle between the equatorial plane and edge of the torus (Δ), ratio of the maximum to minimum radii of the torus ($R_{\text{max}}/R_{\text{min}}$), the viewing angle (θ), and the AGN fraction in total IR luminosity ($f_{\text{AGN}}$). In order to avoid a degeneracy of AGN templates (see Yang et al. 2020) and to estimate a reliable CF (see Section 3.3), we fixed $R_{\text{max}}/R_{\text{min}}$ and θ that are optimized for type 1 quasars. We note that $R_{\text{max}}/R_{\text{min}}$ and θ are insensitive to the CF at least for type 1 AGNs as Stalevski et al. (2012) reported.

In X-CIGALE, the polar dust emission is implemented as a graybody emission with an empirical extinction curve (see Section 2.4 in Yang et al. 2020, for more details). The graybody is formulated as $1 - e^{-\tau(v)} B_{\nu}(\text{polar})$, where $\nu$ is the frequency, $\tau$ is the emissivity index of the dust, and $B_{\nu}(\text{polar})$ is the Planck function. $\tau \equiv (\nu/\nu_0)^{\beta}$ is the optical depth, $\nu_0$ is the frequency where optical depth equals unity (Draine 2006). $\nu_0 = 1.5$ THz ($\lambda_0 = 200$ μm) in X-CIGALE, and β is fixed to be 1.6 (e.g. Casey 2012), and thus we parameterized $\tau_{\text{polar}}$ in the same manner as Toba et al. (2020b). We adopted the SMC extinction curve (Prevot et al. 1984) that may be reasonable for AGN dust (e.g., Pitman et al. 2000; Kuhn et al. 2001; Salvato et al. 2009), in which we parameterized $E(B-V) = 0.50$ means that the polar dust component is not necessary. We confirmed that our conclusion is not significantly affected if we assumed another extinction curve.

In the framework of our SED modeling, IR luminosity can be described by a combination of stellar component ($L_{\text{IR}}^{\text{stellar}}$), AGN accretion disk component ($L_{\text{IR}}^{\text{disk}}$), AGN dust torus component ($L_{\text{IR}}^{\text{torus}}$), and AGN polar dust component ($L_{\text{IR}}^{\text{polar}}$), which enables us to estimate $L_{\text{IR}}^{\text{stellar}}$ that is relevant to the CF through the SED decomposition.

Under the parameter setting described in Table 1, we fit the stellar and AGN (accretion disk, dust torus, and polar) components to at most 13 photometric data as described in Section 2.2. Although the photometry employed in DR16Q is not identical, the profile-fit photometry is used for the SDSS and 2MASS (Lyke et al. 2020), while the UKIDSS and unWISE data are forced photometry at the SDSS centroids (Aihara et al. 2011; Lang 2014). Therefore, the flux densities in the optical–MIR bands in DR16Q are expected to trace the total flux densities, suggesting that the influence of different photometry is likely to be small (see also Section 4.5). We used flux density in a band when the signal-to-noise ratio (S/N) is greater than 3 at that band. Following Toba et al. (2019a), we put $3\sigma$ upper limits for objects with ph Qual = “U” (which means upper limit on magnitude) in the MIR bands.

### 2.4. Optical Spectral Fitting with QSFit

In order to derive $M_{\text{BH}}$, $L_{\text{bol}}$, and $\lambda_{\text{edd}}$ of our quasar sample, we conducted a spectral fitting to SDSS spectra by using the Quasar Spectral Fitting package (QSFit v1.3.0; Calderone et al. 2017). This code fits optical spectra by taking into account (i) AGN continuum with a single power-law, (ii) Balmer continuum modeled by Grandi (1982) and Dietrich et al. (2002), (iii) the host galaxy component with an empirical SED template, (iv) iron blended emission lines with UV–optical templates (Vestergaard & Wilkes 2001; Véron-Cetty et al. 2004), and (v) emission lines with Gaussian components. QSFit fits all the components simultaneously following a Levenberg–Marquardt least-squares minimization algorithm with the MPFIT (Markwardt 2009) procedure.

The main purpose of this spectral fitting is to measure the FWHM of the Hβ broad component ($FWHM_{H\beta}$) and continuum luminosity at 5100 Å ($L_{5100}$), which are ingredients for $M_{\text{BH}}$ estimates. For the host galaxy contribution, we employed a simulated 5 Gyr old elliptical galaxy template (Silva et al. 1998; Polletta et al. 2007), allowing the normalization to vary. After correcting the Galactic extinction provided by Schlafly & Finkbeiner (2011), which is the same as what we adopted for the SDSS photometry (see Section 2.2), spectral fitting was executed. Following Calderone et al. (2017), we fit the Hβ line with narrow and broad components in which the FWHM of narrow and broad components is constrained in the range of 100–1000 km s$^{-1}$ and 900–15,000 km s$^{-1}$, respectively, to allow a good decomposition of the line profile.

Based on outputs from QSFit, we estimated $M_{\text{BH}}$ with a single-epoch method reported by Vestergaard & Peterson (2006):

$$\log \left( \frac{M_{\text{BH}}}{M_\odot} \right) = \log \left( \frac{FWHM_{H\beta}}{1000 \text{ km s}^{-1}} \right)^2 \left( \frac{L_{5100}}{10^{44} \text{ erg s}^{-1}} \right)^{0.50} + (6.91 \pm 0.02).$$

$L_{\text{bol}}$ was converted from $BC_{5100} \times L_{5100}$ where $BC_{5100} = 8.1 \pm 0.4$ is the bolometric correction (Runnoe et al. 2012). The uncertainty in $M_{\text{BH}}$ is calculated through error propagation of Equation (1), while the uncertainty in $L_{\text{bol}}$ is propagated from 1σ errors of $L_{5100}$ and $BC_{5100}$.

### 3. Results

Here we present physical properties of 37,181 quasars that are derived from the SED fitting with X-CIGALE and spectral fitting with QSFit, which are summarized in Table 4.

---

16 https://qsfit.inaf.it

17 Since QSFit allows us to fit the host galaxy component for objects at $z < 0.8$ by default (see Section 2.4 in Calderone et al. 2017), our spectral fitting to the quasar sample at $z < 0.7$ always takes into account the contribution of the host galaxy to the continuum.

18 Rakshit et al. (2020) reported that multiple Gaussians are often required to fit the broad component, and fitting the broad component with a single Gaussian would not provide proper FWHM measurements for some cases, which should be kept in mind for this work.
3.1. Result of the SED Fitting and Bayesian Information Criterion

Figure 2 shows examples of the SED fitting with X-CIGALE. We confirm that 34,541/37,181 (∼92.9%) objects have reduced \( \chi^2_{\text{CIGALE}} < 3.0 \), meaning that the data are well fitted with the combination of the stellar, nebular, AGN accretion disk, dust torus, and polar dust components by X-CIGALE.

On the other hand, it is worth investigating whether the polar dust component (which is the main topic in this work) is practically needed to improve the SED fitting. In order to test the requirement to add an AGN polar dust component to the SED fitting, we calculate the Bayesian information criterion (BIC; Schwarz 1978) for two fits that are derived with and without the polar dust component. The BIC is defined as \( \text{BIC} = \chi^2 + k \times \ln(n) \), where \( \chi^2 \) is the nonreduced chi-square, \( k \) is the number of degrees of freedom (dof), and \( n \) is the number of photometric data points used for the fitting. We then compare the results of two SED fittings without/with the polar dust component by using \( \Delta \text{BIC} = \text{BIC}_{\text{wpolar}} - \text{BIC}_{\text{wpolar}} \).

The resultant \( \Delta \text{BIC} \) tells whether or not the AGN polar dust component is required to give a better fit, taking into account the difference in dof (e.g., Ciesla et al. 2018; Buat et al. 2019; Aufort et al. 2020; Toba et al. 2020a).

Figure 3 shows the histogram of \( \Delta \text{BIC} \) for our quasar sample. We adopt \( \Delta \text{BIC} = 6 \) as a threshold to consider the differences in two fits in the same manner as Buat et al. (2019). If \( \Delta \text{BIC} > 6 \), this indicates that adding the AGN polar dust component significantly improves the fit. We find that about 30.0% of objects satisfy \( \Delta \text{BIC} > 6 \). This suggests that for a faction of objects in our SDSS quasar sample at \( z < 0.7 \), an AGN polar dust component may not be necessary. We note that the threshold we adopted in this work is conservative compared to what was originally suggested, \( \Delta \text{BIC} = 2 \) (Liddle 2004; Stanley et al. 2015). Nevertheless, the above result could suggest that our SED modeling may not be enough to constrain the AGN polar dust emission given a limited number of photometric data in the MIR regime, which we should keep in mind for the following analysis.

We remind that the main purpose of this work is to see how the AGN polar dust would affect the CF of type 1 quasars. Hence, we consider objects with \( \chi^2_{\text{CIGALE}} < 3.0 \) and \( \Delta \text{BIC} > 6 \) for the correlation analysis (see Section 3.3).
3.2. Result of the Spectral Fitting

Figure 4 shows examples of the optical spectral fitting with QSFit. We confirm that 36,855/37,181 (~99.1%) objects have reduced \( \chi^2_{	ext{QSFIT}} < 3.0 \), while only 170 (~0.5%) objects are failed to fit owing to low S/N. This indicates that the SDSS spectra of our sample are well fitted by QSFit. Note that objects shown in the top panel of Figure 4 are expected to have a large contribution from the host galaxy to optical spectrum according to the SED fitting (see top panel in Figure 2). We confirm that this is the case for their optical spectra, suggesting that our SED modeling and spectral fitting give consistent results.

In addition to goodness of fitting (i.e., \( \chi^2_{	ext{QSFIT}} \)), QSFit provides “quality flags” for measurements to assess the reliability of the results (see Appendix C in Calderone et al. 2017, for more details). We considered \( \text{Cont}_5100_{\text{Qual}} \) and \( \text{HB}_{{BR}_{\text{Qual}}} \), which are relevant to the reliability of \( M_{\text{BH}} \) and \( L_{\text{bol}} \) (see also Table 4). We find that \( L_{5100} \) and \( \text{FWHM}_{\text{H}} \) are securely estimated for 21,888/37,181 (~58.9%) objects. To ensure the accuracy of fitting results, we focus on objects with \( \chi^2_{\text{QSFIT}} < 3.0 \), \( \text{Cont}_5100_{\text{Qual}} = 0 \), and \( \text{HB}_{{BR}_{\text{Qual}}} = 0 \) for the following analysis (see Section 3.3).

The distributions of our sample with \( \text{Cont}_5100_{\text{Qual}} = 0 \) and \( \text{HB}_{{BR}_{\text{Qual}}} = 0 \) in the \( z - L_{\text{bol}} \) and \( M_{\text{BH}} - L_{\text{bol}} \) planes are shown in Figures 5 and 6, respectively. The mean and standard deviation of \( \log L_{\text{bol}} \) (erg s\(^{-1}\)), \( \log(M_{\text{BH}}/M_\odot) \), and \( \log \lambda_{\text{Edd}} \) are 45.0 ± 0.46, 8.29 ± 0.45, and −1.41 ± 0.38, respectively.

3.3. Dependences of the CF on \( L_{\text{bol}}, M_{\text{BH}}, \) and \( \lambda_{\text{Edd}} \)

We investigate the dependences of the CF on \( L_{\text{bol}}, M_{\text{BH}}, \) and \( \lambda_{\text{Edd}} \) of our quasar sample. As mentioned in Sections 3.1 and 3.2, quasars with (i) \( \chi^2_{\text{CIGALE}} < 3.0 \), (ii) \( \Delta\text{BIC} > 6 \), (iii) \( \chi^2_{\text{QSFIT}} < 3.0 \), (iv) \( \text{Cont}_5100_{\text{Qual}} = 0 \), and (v) \( \text{HB}_{{BR}_{\text{Qual}}} = 0 \) are used for the following correlation analysis, which yields 5752 objects (see also Figure 1). We discuss how the above selection cuts affect the dependences of the CF in Section 4.2. Their distributions of our subsample in the \( z - L_{\text{bol}} \) and \( M_{\text{BH}} - L_{\text{bol}} \) planes are also shown in Figures 5 and 6, respectively. We find that our quasar sample selected from the DR16Q covers 43.5 < \( \log L_{\text{bol}} \) (erg s\(^{-1}\)) < 46.4, 6.57 < \( \log(M_{\text{BH}}/M_\odot) \) < 9.89, and −3.16 < \( \log \lambda_{\text{Edd}} \) < −0.22. The mean and standard deviation of \( \log L_{\text{bol}} \) (erg s\(^{-1}\)), \( \log(M_{\text{BH}}/M_\odot) \), and \( \log \lambda_{\text{Edd}} \) are 45.0 ± 0.39, 8.29 ± 0.46, and −1.42 ± 0.38, respectively. The fact that the DR16Q contains fainter quasars than those in previous releases enables us to investigate the CF for less luminous quasars with less massive BH and smaller accretion rate compared to previous studies based on the SDSS quasar catalogs (e.g., Gu 2013; Ma & Wang 2013).

As we cautioned in Section 1, the IR-to-bolometric luminosity ratio would not always be a good tracer of the CF. We hence converted from \( L_{\text{IR}}/L_{\text{bol}} \) to CF by using a
Figure 5. Bolometric luminosity as a function of redshift for our sample. The histograms of redshift and $L_{\text{bol}}$ are attached on the top and right, respectively. The gray and red contours represent the number density of 21,888 objects with $\text{Cont}_{5100,\text{Qual}} = 0$ and $\text{HB BR Qual} = 0$ and 5752 objects for correlation analysis, respectively, in each $0.4 \times 0.4$ region on the $z - \log L_{\text{bol}}$ plane. Objects within the blue dotted square are used to test the influence of the Malmaquais bias on correlation analysis (see Section 4.2.3).

Figure 6. BH mass and bolometric luminosity of our sample. The histograms of $M_{\text{BH}}$ and $L_{\text{bol}}$ are attached on the top and right, respectively. The gray and red contours represent the number density of 21,888 objects with $\text{Cont}_{5100,\text{Qual}} = 0$ and $\text{HB BR Qual} = 0$ and 5752 objects for correlation analysis, respectively, in each $0.4 \times 0.4$ region on the $\log M_{\text{BH}} - \log L_{\text{bol}}$ plane. The blue diagonal lines show Eddington ratio of $\lambda_{\text{Edd}} = -3, -2, -1, 0$ and from bottom right to top left.

nonlinear relation in Stalevski et al. (2016), who provides conversion formulae assuming SKIRTOR with $R_{\text{max}} / R_{\text{min}} = 30$ and $\theta = 0^\circ$ that are the same as in Table 1 (see also the middle panel of Figure 7 in Stalevski et al. 2016):

$$
\text{CF} = a_0 + a_1 \left( \frac{L_{\text{IR}}}{L_{\text{bol}}} \right)^4 + a_2 \left( \frac{L_{\text{IR}}}{L_{\text{bol}}} \right)^3 + a_3 \left( \frac{L_{\text{IR}}}{L_{\text{bol}}} \right)^2 + a_4 \left( \frac{L_{\text{IR}}}{L_{\text{bol}}} \right) + a_5.
$$

Since we parameterized $\tau_{9.7}$ (see Table 1), we chose $(a_0, a_1, a_2, a_3, a_4) = (0.192478, 1.40827, -1.48727, 0.875215, -0.177798), (0.195615, 1.20218, -1.04546, 0.47493, -0.0601471), \text{and } (0.196387, 1.02696, -0.782418, 0.299937, -0.0255416)$ for objects with $\tau_{9.7} = 3, 5,$ and 9, respectively. The uncertainty of the CF was propagated from a relative error of $L_{\text{IR}} / L_{\text{bol}}$.

Figure 7 shows the relation between the CF of dust torus and AGN properties, i.e., $CF - L_{\text{bol}}, CF - M_{\text{BH}}$, and $CF - \lambda_{\text{Edd}}$ for 5752 quasars. We confirm an anticorrelation of the above three quantities, which is consistent with recent works (Ezhikode et al. 2017; Ricci et al. 2017; Zhuang et al. 2018). We also investigate the dependence of the CF of polar dust (CFPD) on $L_{\text{bol}}, M_{\text{BH}}$, and $\lambda_{\text{Edd}}$, which is shown in Figure 7. We find that CFPD also clearly depends on AGN properties (see Section 4 for quantitative discussion).

4. Discussion

First, we discuss how the AGN polar dust affects the correlation coefficient of dust CF and AGN properties such as $L_{\text{bol}}, M_{\text{BH}}$, and $\lambda_{\text{Edd}}$. We then discuss possible selection effects and uncertainties of the CF and correlation analysis through Monte Carlo simulation and mock analysis. Finally, we discuss the dependence of the CF–$\lambda_{\text{Edd}}$ correlation on $L_{\text{bol}}, M_{\text{BH}}$, and redshift of our sample.

4.1. Correlation Analysis

To quantify the anticorrection shown in Figure 7, we conducted a correlation analysis for the subsample of 5752 quasars by using a Bayesian maximum likelihood method provided by Kelly (2007), providing a correlation coefficient ($r$) that takes into account uncertainty on both the $x$ and $y$ values (see, e.g., Mateos et al. 2015; Toba et al. 2019a). The same analysis was done for the same subsample of 5752 quasars whose CF was derived by the SED fitting without adding the polar dust component in order to check how the presence or absence of polar dust would affect the correlation strength. The resultant correlation coefficients are summarized in Table 2.

Figure 8 shows the correlation coefficient ($r$) of CF–$L_{\text{bol}}, CF - M_{\text{BH}},$ and CF–$\lambda_{\text{Edd}}$ with and without adding the AGN polar dust component to the SED fitting. We find that the $|r|$ values of objects when considering polar dust emission are larger than those without considering the polar dust. In particular, the influence of the polar dust component on the correlation strength may be significant for CF–$\lambda_{\text{Edd}}$ rather than CF–$L_{\text{bol}}$ and CF–$M_{\text{BH}}$. This indicates that polar dust wind, probably driven by radiation pressure from the AGN, may be crucial for regulating obscuring dusty structure surrounding SMBHs. Table 2 also provides insight into the properties of polar dust; CFPD seems to strongly depend on $L_{\text{bol}}$ and $\lambda_{\text{Edd}}$ rather than $M_{\text{BH}}$, which is consistent with what we discussed above. Strong radiation pressure from luminous quasars with high $\lambda_{\text{Edd}}$ may blow out dust in the polar direction.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|}
\hline
 & $r$ without Polar Dust & $r$ with Polar Dust \\
\hline
CF–$L_{\text{bol}}$ & $-0.54 \pm 0.01$ & $-0.75 \pm 0.03$ \\
CF–$M_{\text{BH}}$ & $-0.50 \pm 0.01$ & $-0.58 \pm 0.03$ \\
CF–$\lambda_{\text{Edd}}$ & $0.01 \pm 0.02$ & $-0.21 \pm 0.04$ \\
CFPD–$L_{\text{bol}}$ & $\ldots$ & $-0.89 \pm 0.01$ \\
CFPD–$M_{\text{BH}}$ & $\ldots$ & $-0.46 \pm 0.03$ \\
CFPD–$\lambda_{\text{Edd}}$ & $\ldots$ & $-0.58 \pm 0.02$ \\
\hline
\end{tabular}
\caption{Summary of the Correlation Coefficient ($r$)}
\end{table}

Note. CF and CFPD denote the covering factor of dust torus and polar dust, respectively.
which would be associated with an AGN-driven outflow (e.g., Schartmann et al. 2014). This suggests that CFPD is regulated by \(L_{\text{bol}}\) and possibly \(\lambda_{\text{Edd}}\).

4.2. Selection Bias

4.2.1. Parent SDSS Quasar Sample

We used 37,181 quasars at \(z < 0.7\) drawn from the SDSS DR16Q as a parent sample (see Figure 1). Since the completeness and contamination rate of the parent sample would directly affect our correlation analysis, we estimate them following Lyke et al. (2020). We utilized 323 objects with \texttt{RANDOM\_SELECT = 1} that are randomly selected from the DR16Q. This subsample was visually inspected to check whether the pipeline correctly classified the spectrum. If an object is visually confirmed to be a quasar, the object has \texttt{IS\_QSO\_10K = 1}. The confidence rating for a visually identified redshift is stored in \texttt{Z\_CONF\_10K}. We consider objects with \texttt{Z\_CONF\_10K > 2} as those with correct redshift (see Section 3.3 in Lyke et al. 2020, for more details).

The completeness and contamination rate of the parent sample estimated based on Equations (1) and (2) in Lyke et al. (2020) are 99.7% and 0.3%, respectively. This means that the parent quasar sample in this work has quite high completeness and purity, which may not affect our conclusion in this work.

4.2.2. Malmquist Bias

Because the target selection for quasars proceeded from flux-limited samples (e.g., Myers et al. 2015), our correlation analysis would be affected by Malmquist bias (see also Figure 5). In order to see how the Malmquist bias would affect the correlation coefficients, we created a subsample that is expected not to be affected by the Malmquist bias in which 4828 objects with \(4.2 < \log L_{\text{bol}} < 45.5\) and \(z > 0.3\) were extracted (see the blue dotted square in Figure 5). We then conducted the correlation analysis for the subsample in the same manner as was described in Section 4.1. We find that the mean and standard deviations of \(r\) for \(\text{CF} - L_{\text{bol}}, \text{CF} - M_{\text{BH}},\) and \(\text{CF} - \lambda_{\text{Edd}}\) are \(-0.94 \pm 0.04, -0.73 \pm 0.10,\) and \(-0.32 \pm 0.17,\) respectively. The absolute values of \(r\) tend to be higher than what is reported in Table 2, although there are large standard deviations, particularly for \(r(\text{CF} - M_{\text{BH}})\) and \(r(\text{CF} - \lambda_{\text{Edd}})\). This result would indicate that Malmquist bias makes the correlation strength weaker.

4.2.3. Subsample of Quasars

As described in Sections 3.1 and 3.2, we created a subsample for the correlation analysis by considering the reduced \(\chi^2_{\text{CIGALE}},\) \(\Delta \text{BIC},\) \texttt{Cont\_5100\_Qual}, and \texttt{HB\_BR\_Qual} to understand how AGN polar dust affects dust CF. In particular, the threshold of \(\Delta \text{BIC}\) contributed to a decrease in the sample size of quasars from 37,181 to 5752, although the size of the sample is still large enough for statistical investigation. We

Figure 7. Relation between the CF and (a) \(\log L_{\text{bol}},\) (b) \(\log M_{\text{BH}},\) and (c) \(\log \lambda_{\text{Edd}}\) for 5752 quasars at \(z < 0.7.\) Reddish symbols and lines represent the CF of dust torus, while green lines represent the CF of polar dust. Magenta points represent data, while red circles represent weighted mean and standard deviation. Red and green lines with shaded region denote the best-fit relations with 1σ uncertainty.

Figure 8. Correlation coefficient \((r)\) of \(\text{CF} - L_{\text{bol}}, \text{CF} - M_{\text{BH}},\) and \(\text{CF} - \lambda_{\text{Edd}}\). Values of \(r\) with and without adding the AGN polar dust component to the SED fitting are plotted in red and blue, respectively.
discuss how the selection criteria for the correlation analysis would be biased toward the resultant correlation coefficient. To address this issue, we performed a Monte Carlo simulation in which we randomly chose a set of threshold values (reduced $\chi^2_{\text{CIGALE}}$, reduced $\chi^2_{\text{QSFit}}$, and $\Delta\text{BIC}$) and conducted the correlation analysis. We iterated the above process 1000 times where calculation was executed only if the sample size exceeds 1000 in order to ensure reliability of the resultant correlation coefficient.

Figure 9 shows the distribution of $r$. The mean and standard deviations of $r$ for $\text{CF}–L_{\text{bol}}$, $\text{CF}–M_{\text{BH}}$, and $\text{CF}–\lambda_{\text{Edd}}$ are $-0.84 \pm 0.10$, $-0.67 \pm 0.13$, and $-0.26 \pm 0.13$, respectively, which are roughly consistent with what we obtained in this work (see Table 2). This suggests that selection bias caused by adopting threshold values in this work does not significantly affect the result of the correlation analysis.

4.3. Influence of a Limited Number of Stellar Templates on the Correlation Coefficients

For the SED and spectral fitting in a consistent manner, we fixed the age of the main stellar population to be 5.0 Gyr for the SED fitting, while we used the template of an elliptical galaxy with a stellar age of 5.0 Gyr for the spectral fitting (see Sections 2.3 and 2.4). Although this assumption (i.e., low-z quasars are hosted by elliptical galaxies) is expected to apply to the majority of our quasar sample (e.g., Bahcall et al. 1997; Dunlop et al. 2003; Kauffmann et al. 2003; Floyd et al. 2004), a fraction of quasars could not be the case (e.g., McLure et al. 1999; Schawinski et al. 2010; Ishino et al. 2020). How would these possible variations of quasar host properties affect resulting correlation coefficients?

To address this issue, we modified (i) the parameter ranges in the age of the main stellar population used for the SED fitting and (ii) AGN host templates for the spectral fitting. For the SED fitting, we allowed the age of the main stellar population to vary from 1.0 to 11.0 Gyr at intervals of 2.0 Gyr. For the spectral fitting, we utilized host galaxy templates of a simulated 2.0 Gyr old elliptical galaxy, S0 galaxy, and three types of spiral galaxies (i.e., Sa, Sb, and Sc; Polletta et al. 2007), in addition to the 5.0 Gyr old elliptical galaxy template we originally used. We randomly chose a host galaxy template from the above options. We then performed the SED fitting and spectral fitting in the same manner as was described in Sections 2.3 and 2.4. We iterated this process 1000 times and estimated the distribution of $r$.

The resulting distributions of $r$ are shown in Figure 10. We find that the mean and standard deviations of $r$ for $\text{CF}–L_{\text{bol}}$, $\text{CF}–M_{\text{BH}}$, and $\text{CF}–\lambda_{\text{Edd}}$ are $-0.79 \pm 0.00$, $-0.62 \pm 0.01$, and $-0.24 \pm 0.01$, respectively, which are in good agreement with what we obtained in this work (see Table 2). Therefore, we conclude that the influence of a limited number of stellar templates on the correlation coefficients is likely to be small.

4.4. Influence of $\text{CF}–L_{\text{bol}}$ Correlation on $\text{CF}–\lambda_{\text{Edd}}$ Correlation Coefficient

We reported in Section 4.1 that CF depends on $\lambda_{\text{Edd}}$ by taking into account polar dust emission. It should be noted that $\lambda_{\text{Edd}}$ is directly related to $L_{\text{bol}}$ that strongly correlates with the CF, which would induce an artificial correlation of $\text{CF}–\lambda_{\text{Edd}}$.

To disentangle the dependence and see how $r$ ($\text{CF}–\lambda_{\text{Edd}}$) would be affected by strong correlation of $\text{CF}–L_{\text{bol}}$, we employed a diagnostic method presented in Hasinger (2008), who investigated redshift dependence on CF based on the relation between the CF and X-ray luminosity (see also Toba et al. 2014). First, we estimated the average value of the slope of the relation between the CF and $L_{\text{bol}}$ in the range of $-2.0 < \log \lambda_{\text{Edd}} < 0.0$. We then estimated the normalization value at a luminosity of $\log L_{\text{bol}} = 45.0$ erg s$^{-1}$, in the middle of the observed range, as a function of $\lambda_{\text{Edd}}$ by keeping the slope fixed to the average value. The $\lambda_{\text{Edd}}$ bins were $-2.0 < \log \lambda_{\text{Edd}} < -1.5$, $-1.5 < \log \lambda_{\text{Edd}} < -1.0$, $-1.0 < \log \lambda_{\text{Edd}} < -0.5$, and $-0.5 < \log \lambda_{\text{Edd}} < 0.0$ in the range of $\log L_{\text{bol}} = 44–46$ erg s$^{-1}$. We find that the resulting correlation coefficient
is $r(\text{CF} - \lambda_{\text{Edd}}) \sim -0.31$, which is consistent with what we obtained in Section 4.1. Therefore, we conclude that a strong CF–$L_{\text{bol}}$ correlation may not significantly affect the correlation coefficient of CF–$\lambda_{\text{Edd}}$.

4.5. Mock Analysis

We then check whether or not the derived CF can actually be estimated reliably, given the limited number of photometry and its uncertainty. We execute a mock analysis that is a procedure provided by $X\text{--CIGALE}$ (see, e.g., Buat et al. 2012, 2014; Ciesla et al. 2015; Lo Faro et al. 2017; Boquien et al. 2019; Toba et al. 2019b, 2020a, for more details) for 5752 quasars. This analysis is done by a mock catalog in which a value is taken from a Gaussian distribution with the same standard deviation as the observation is added to each photometry originally used, which would also enable us to test how the difference in photometry influences CF (see Section 2.3).

Figure 11 shows the histogram of differences in CFs that are derived from $X\text{--CIGALE}$ in this work and from the mock catalog. The mean and standard deviations of $\Delta \text{CF} = 0.04 \pm 0.07$, suggesting that the CF of the majority of our quasar sample is insensitive to the limited number of photometric points and difference in photometry.

4.6. Influence of AGN Properties on CF–$\lambda_{\text{Edd}}$ Correlation

In Section 4.1, we report that adding AGN polar dust emission to SED fitting makes anticorrelations of CF–$L_{\text{bol}}$, CF–$M_{\text{BH}}$, and CF–$\lambda_{\text{Edd}}$ stronger than those without adding it. On the other hand, $L_{\text{bol}}$, $M_{\text{BH}}$, $\lambda_{\text{Edd}}$, and also redshift should be correlated with each other as mentioned in Sections 4.2.2 and 4.4 (see also Figures 5 and 6). With all the caveats discussed in Sections 4.2–4.5 in mind, we discuss how the CF–$\lambda_{\text{Edd}}$ correlation depends on AGN properties (i.e., $L_{\text{bol}}$ and $M_{\text{BH}}$) and redshift. The resultant correlation coefficients are summarized in Table 3.

4.6.1. Redshift Dependence

Although we confirm the anticorrelations of CF and $L_{\text{bol}}$, $M_{\text{BH}}$, and $\lambda_{\text{Edd}}$, the correlation strength differs among them. We find that the CF–$L_{\text{bol}}$ correlation is stronger than other two correlations as shown in Table 2 and Figure 8, which seems inconsistent with the X-ray-based work of Ricci et al. (2017), who reported that the CF–$\lambda_{\text{Edd}}$ correlation is stronger than the CF–$L_{\text{bol}}$ correlation. What causes this discrepancy?

There are some possibilities, such as the difference in (i) redshift, (ii) sample selection (i.e., our sample is limited to type 1 quasars, while the sample in Ricci et al. 2017 is not), and (iii) definition of CF (i.e., $L_{\text{IR}}$ $/L_{\text{bol}}$ is employed in this work, while a fraction of X-ray-obscured sources is employed in Ricci et al. 2017). It is hard to quantify, however, the influence of the difference in the sample selection and definition of the CF on the correlation strength, and it is beyond the scope of this work. We thus argue for the possibility that the difference
in redshift could cause the discrepancy. Ricci et al. (2017) targeted nearby AGNs with a median redshift of \( z \approx 0.037 \), whereas we focus on AGNs with much higher redshift up to \( z = 0.7 \).

Figure 12 shows the redshift dependence of the CF–\( \lambda_{\text{Edd}} \) relation. We find that the CF of AGNs with \( z < 0.12 \) (which is similar to that of the sample in Ricci et al. 2017) tends to strongly depend on \( \lambda_{\text{Edd}} \), with a correlation coefficient of \( r = -0.49 \pm 0.32 \), while CF–\( \lambda_{\text{Edd}} \) for AGNs at \( z > 0.2 \) shows weaker correlations than that at \( z < 0.12 \). This indicates that the aforementioned discrepancy can be explained by the difference in redshift between the samples in Ricci et al. (2017) and this work. We also remind that our correlation analysis would be affected by the Malmquist bias, which could make the correlation strength weaker, as discussed in Section 4.2.2.

This result also might suggest that the CF decreases with increasing redshift for at least \( z < 0.7 \), a trend that is consistent with what is reported in Toba et al. (2014), although there is large uncertainty. On the other hand, the fraction of obscured X-ray AGNs increases with redshift for the same luminosity (e.g., Ueda et al. 2014). This discrepancy might be caused by the difference in sample selection and definition of CF.

### 4.6.2. BH Mass Dependence

Recently, Kawakatu et al. (2020) constructed a model of a nuclear starburst disk supported by the turbulent pressure from Type II supernovae and investigated how the CF depends on AGN properties by taking account of anisotropic radiation pressure from AGNs. They found that the CF strongly depends on \( \lambda_{\text{Edd}} \) for AGNs with \( M_{\text{BH}} < 10^6 M_\odot \), while the dependence of the CF on \( \lambda_{\text{Edd}} \) is much weaker for AGNs with \( M_{\text{BH}} > 10^7 - 10^9 M_\odot \). Although they did not incorporate the AGN polar dust outflow, it is worth checking the dependence of the CF–\( \lambda_{\text{Edd}} \) correlation on \( M_{\text{BH}} \).

Figure 13 shows how the difference in \( M_{\text{BH}} \) would affect the correlation strength of CF–\( \lambda_{\text{Edd}} \). The resultant \( r \) of CF–\( \lambda_{\text{Edd}} \) for quasars with \( \log(M_{\text{BH}}/M_\odot) < 8.0 \) and \( \log(M_{\text{BH}}/M_\odot) > 9.0 \) is \(-0.56 \pm 0.07\) and \(-0.50 \pm 0.05\), respectively. This result indicates that the CF of quasars with \( < 10^8 M_\odot \) strongly depends on \( \lambda_{\text{Edd}} \). The overall statistical trend is in good agreement with what was reported in Kawakatu et al. (2020).

### 4.6.3. Bolometric Luminosity Dependence

Figure 14 shows the dependence of \( L_{\text{bol}} \) on CF–\( \lambda_{\text{Edd}} \). We find that the anticorrelation of CF–\( \lambda_{\text{Edd}} \) may disappear for AGNs with \( L_{\text{bol}} > 45.0 \). In this \( L_{\text{bol}} \) range, the correlation coefficients are even positive with large uncertainty (see Table 3). Zhuang et al. (2018) reported that the CF of luminous quasars with \( L_{\text{bol}} \gtrsim 10^{45.0} \) erg s\(^{-1}\) increases with increasing \( \lambda_{\text{Edd}} \); although this positive correlation would appear when \( \log \lambda_{\text{Edd}} \) ranges from \(-0.25\) and \(0.5\). This result could indicate that the overall trend of CF–\( \lambda_{\text{Edd}} \) is determined by AGNs with \( L_{\text{bol}} < 45.0 \).

### 5. Summary

In this paper, we revisit the relationship between the CF and AGN properties (\( L_{\text{bol}}, M_{\text{BH}}, \) and \( \lambda_{\text{Edd}} \)) for type 1 quasars selected from the SDSS DR16 quasar catalog. Thanks to the newly available DR16Q, we can investigate the dependence of the CF for quasars with a wide range in \( L_{\text{bol}}, M_{\text{BH}}, \) and \( \lambda_{\text{Edd}} \). We narrowed down the DR16Q catalog to 37,181 quasars with \( z < 0.7 \) and performed the SED fitting with X–CIGALE to at
most 13 optical–MIR photometry and spectral fittings with QSFit to the SDSS spectra. In particular, we took into account the contribution of AGN polar dust emission to IR luminosity, which could affect the measurement of the CF. For 5752 quasars whose physical quantities estimated by X-CIGALE and QSFit are reliable, we conducted a correlation analysis to see how the AGN polar dust would affect the correlation coefficient. We find that taking into account the contribution of AGN polar dust to IR emission provides stronger anticorrelations of CF–$L_{\text{bol}}$, CF–$M_{\text{BH}}$, and CF–$\lambda_{\text{Edd}}$ than not considering the polar dust. This result indicates that AGN polar dust wind is a key ingredient to regulate the obscuring structure of AGNs.

The authors gratefully acknowledge the anonymous referee for a careful reading of the manuscript and very helpful comments. We also appreciate Dr. Guang Yang for helping with the installation and modification of X-CIGALE.

Funding for the Sloan Digital Sky Survey IV has been provided by the Alfred P. Sloan Foundation, the U.S. Department of Energy Office of Science, and the Participating Institutions. SDSS-IV acknowledges support and resources from the Center for High-Performance Computing at the University of Utah. The SDSS website is www.sdss.org. SDSS-IV is managed by the Participating Institutions of the SDSS Collaboration, including the Brazilian Participation Group, the Carnegie Institution for Science, Carnegie Mellon University, the Chilean Participation Group, the French Participation Group, Harvard-Smithsonian Center for Astrophysics, Instituto de Astrofisica de Canarias, Johns Hopkins University, Kavli Institute for the Physics and Mathematics of the Universe (IPMU)/University of Tokyo, the Korean Participation Group, Lawrence Berkeley National Laboratory, Leibniz Institut für Astrophysik Potsdam (AIP), Max-Planck-Institut für Astronomie (MPIA Heidelberg), Max-Planck-Institut für Astrophysik (MPA Garching), Max-Planck-Institut für Extraterrestrische Physik (MPE), National Astronomical Observatories of China, New Mexico State University, New York University, University of Notre Dame, Observatório Nacional/MCTI, The Ohio State University, Pennsylvania State University, Shanghai Astronomical Observatory, United Kingdom Participation Group, Universidad Nacional Autónoma de México, University of Arizona, University of Colorado Boulder, University of Oxford, University of Portsmouth, University of Utah, University of Virginia, University of Washington, University of Wisconsin, Vanderbilt University, and Yale University.

This publication makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation.

This work is based in part on data obtained as part of the UKIRT Infrared Deep Sky Survey.

This publication makes use of data products from the Wide-field Infrared Survey Explorer, which is a joint project of the University of California, Los Angeles, and the Jet Propulsion Laboratory/California Institute of Technology, funded by the National Aeronautics and Space Administration.

Numerical computations/simulations were carried out (in part) using the SuMIRe cluster operated by the Extragalactic OIR group at ASIAA.

This work is supported by JSPS KAKENHI grant Nos. 18J01050 and 19K14759 (Y.T.), 17K05384 and 20H01946 (Y.U.), and 20H01949 (T.N.).

Facilities: Sloan, CTIO:2MASS, FLWO:2MASS, UKIRT, WISE.

Software: IDL, IDL Astronomy User’s Library (Landsman et al. 1993), X-CIGALE (Boquien et al. 2019, Yang et al. 2020), QSFit (Calderone et al. 2017), TOPCAT (Taylor 2006).

Appendix

A Value-added Catalog for SDSS DR16 Quasars at $z < 0.7$

We provide physical properties of 37,181 quasars at $z < 0.7$ selected from the SDSS DR16Q. The catalog description is summarized in Table 4.

| Column Name | Format | Unit | Description |
|-------------|--------|------|-------------|
| SpecObjID   | STRING |      | Unique ID in the SDSS DR16 |
| Plate       | INT32 |     | Spectroscopic plate number |
| MJD         | INT32 |     | Modified Julian day of the spectroscopic observation |
| FiberID     | INT16 |      | Fiber ID number |
| R.A.        | DOUBLE | degree | Right ascension (J2000.0) from the SDSS DR16Q |
| Decl.       | DOUBLE | degree | Declination (J2000.0) from the SDSS DR16Q |
| Redshift    | DOUBLE |      | Redshift (which is taken from column “Redshift” in the SDSS DR16Q) |
| rechi2_QSFit| DOUBLE |      | Reduced $\chi^2$ derived from QSFit |
| Cont_L3000  | DOUBLE | erg s$^{-1}$ | AGN continuum luminosity at the rest-frame 3000 Å derived from QSFit |
| Column Name | Format   | Unit   | Description                                                                 |
|-------------|----------|--------|-----------------------------------------------------------------------------|
| Cont_L3000 | DOUBLE   | erg s⁻¹| Uncertainty of Cont_L3000 derived from QSFit                                 |
| Slope_3000 | DOUBLE   |        | AGN continuum slope at the rest-frame 3000 Å derived from QSFit             |
| Slope_3000 | DOUBLE   |        | Uncertainty of Slope_3000 derived from QSFit                               |
| Cont_3000_Qual | INT32 |        | Quality flag of continuum at the rest-frame 3000 Å derived from QSFit (see Appendix A (xix) in Calderone et al. 2017) |
| Cont_L5100 | DOUBLE   | erg s⁻¹| AGN continuum luminosity at the rest-frame 5100 Å derived from QSFit        |
| Cont_L5100 | DOUBLE   | erg s⁻¹| Uncertainty of Cont_L5100 derived from QSFit                                |
| Slope_5100 | DOUBLE   |        | AGN continuum slope at the rest-frame 5100 Å derived from QSFit             |
| Slope_5100 | DOUBLE   |        | Uncertainty of Slope_5100 derived from QSFit                               |
| Cont_5100_Qual | INT32 |        | Quality flag of continuum at the rest-frame 5100 Å derived from QSFit (see Appendix A (xix) in Calderone et al. 2017) |
| Lum_MgII  | DOUBLE   | erg s⁻¹| Line luminosity of Mg II derived from QSFit                                   |
| Lum_MgII | DOUBLE   | erg s⁻¹| Uncertainty of Lum_MgII derived from QSFit                                    |
| FWHM_MgII | DOUBLE   | km s⁻¹ | FWHM of Mg II derived from QSFit                                              |
| FWHM_MgII | DOUBLE   | km s⁻¹ | Uncertainty of FWHM_MgII derived from QSFit                                  |
| EW_MgII   | DOUBLE   | Å       | Equivalent width of Mg II derived from QSFit                                |
| EW_MgII | DOUBLE   | Å       | Uncertainty of EW_MgII derived from QSFit                                   |
| MgII_Qual | INT32    |        | Quality flag of Mg II line derived from QSFit                               |
| Lum_HB_BR | DOUBLE   | erg s⁻¹| Line luminosity of Hβ (broad component) derived from QSFit                  |
| Lum_HB_BR | DOUBLE   | erg s⁻¹| Uncertainty of Lum_HB_BR derived from QSFit                                  |
| FWHM_HB_BR | DOUBLE   | km s⁻¹ | FWHM of Hβ (broad component) derived from QSFit                             |
| FWHM_HB_BR | DOUBLE   | km s⁻¹ | Uncertainty of FWHM_HB_BR derived from QSFit                                |
| EW_HB_BR  | DOUBLE   | Å       | Equivalent width of Hβ (broad component) derived from QSFit                 |
| EW_HB_BR | DOUBLE   | Å       | Uncertainty of EW_HB_BR derived from QSFit                                  |
| HB_BR_Qual | INT32    |        | Quality flag of Hβ (broad component) line derived from QSFit (see Appendix A (xxxvi) in Calderone et al. 2017) |
| Lum_HB_NA | DOUBLE   | erg s⁻¹| Line luminosity of Hβ (narrow component) derived from QSFit                |
| Lum_HB_NA | DOUBLE   | erg s⁻¹| Uncertainty of Lum_HB_NA derived from QSFit                                 |
| FWHM_HB_NA | DOUBLE   | km s⁻¹ | FWHM of Hβ (narrow component) derived from QSFit                           |
| FWHM_HB_NA | DOUBLE   | km s⁻¹ | Uncertainty of FWHM_HB_NA derived from QSFit                                |
| EW_HB_NA  | DOUBLE   | Å       | Equivalent width of Hβ (narrow component) derived from QSFit               |
| EW_HB_NA | DOUBLE   | Å       | Uncertainty of EW_HB_NA derived from QSFit                                  |
| HB_NA_Qual | INT32    |        | Quality flag of Hβ (narrow component) line derived from QSFit (see Appendix A (xxxvi) in Calderone et al. 2017) |
| Lum_OIII_NA | DOUBLE   | erg s⁻¹| Line luminosity of [O III] λ5007 (narrow component) derived from QSFit     |
| Lum_OIII_NA | DOUBLE   | erg s⁻¹| Uncertainty of Lum_OIII_NA derived from QSFit                               |
| FWHM_OIII_NA | DOUBLE   | km s⁻¹ | FWHM of [O III] λ5007 (narrow component) derived from QSFit                |
| FWHM_OIII_NA | DOUBLE   | km s⁻¹ | Uncertainty of FWHM_OIII_NA derived from QSFit                              |
| EW_OIII_NA  | DOUBLE   | Å       | Equivalent width of [O III] λ5007 (narrow component) derived from QSFit    |
| EW_OIII_NA | DOUBLE   | Å       | Uncertainty of EW_OIII_NA derived from QSFit                                |
| OIII_NA_Qual | INT32    |        | Quality flag of [O III] λ5007 (narrow component) line derived from QSFit (see Appendix A (xxxvi) in Calderone et al. 2017) |
| Lum_OIII_BW | DOUBLE   | erg s⁻¹| Line luminosity of [O III] λ5007 (blue wing component) derived from QSFit |
| Lum_OIII_BW | DOUBLE   | erg s⁻¹| Uncertainty of Lum_OIII_BW derived from QSFit                               |
| FWHM_OIII_BW | DOUBLE   | km s⁻¹ | FWHM of [O III] λ5007 (blue wing component) derived from QSFit             |
| FWHM_OIII_BW | DOUBLE   | km s⁻¹ | Uncertainty of FWHM_OIII_BW derived from QSFit                              |
| EW_OIII_BW  | DOUBLE   | Å       | Equivalent width of [O III] λ5007 (blue wing component) derived from QSFit |
| EW_OIII_BW | DOUBLE   | Å       | Uncertainty of EW_OIII_BW derived from QSFit                                |
| Voff_OIII_BW | DOUBLE   | km s⁻¹ | Velocity offset of [O III] λ5007 (blue wing component) derived from QSFit |
| Voff_OIII_BW | DOUBLE   | km s⁻¹ | Uncertainty of Voff_OIII_BW derived from QSFit                              |
| OIII_BW_Qual | INT32    |        | Quality flag of [O III] λ5007 (blue wing component) line derived from QSFit (see Appendix A (xxxvi) in Calderone et al. 2017) |
| Lum_HA_BR  | DOUBLE   | erg s⁻¹| Line luminosity of Hα (broad component) derived from QSFit                  |
| Lum_HA_BR | DOUBLE   | erg s⁻¹| Uncertainty of Lum_HA_BR derived from QSFit                                  |
| FWHM_HA_BR | DOUBLE   | km s⁻¹ | FWHM of Hα (broad component) derived from QSFit                             |
| FWHM_HA_BR | DOUBLE   | km s⁻¹ | Uncertainty of FWHM_HA_BR derived from QSFit                                |
| EW_HA_BR  | DOUBLE   | Å       | Equivalent width of Hα (broad component) derived from QSFit                 |
| EW_HA_BR | DOUBLE   | Å       | Uncertainty of EW_HA_BR derived from QSFit                                  |
| HA_BR_Qual | INT32    |        | Quality flag of Hα (broad component) line derived from QSFit (see Appendix A (xxxvi) in Calderone et al. 2017) |
| Lum_HA_NA  | DOUBLE   | erg s⁻¹| Line luminosity of Hα (narrow component) derived from QSFit                 |
| Lum_HA_NA | DOUBLE   | erg s⁻¹| Uncertainty of Lum_HA_NA derived from QSFit                                  |
Table 4 (Continued)

| Column Name          | Format  | Unit          | Description                                                                 |
|----------------------|---------|---------------|-----------------------------------------------------------------------------|
| FWHM_HA_NA           | DOUBLE  | km s⁻¹        | FWHM of Hα (narrow component) derived from QSFit                             |
| FWHM_HA_NA_err       | DOUBLE  | km s⁻¹        | Uncertainty of FWHM_HA_NA derived from QSFit                                |
| EW_HA_NA             | DOUBLE  | Å             | Equivalent width of Hα (narrow component) derived from QSFit                |
| EW_HA_NA_err         | DOUBLE  | Å             | Uncertainty of EW_HA_NA derived from QSFit                                  |
| HA_NA_Qual           | INT32   |               | Quality flag of Hα (narrow component) line derived from QSFit (see Appendix A (xxxvi) in Calderone et al. 2017) |
| log_M BH             | DOUBLE  | M☉           | Black hole mass (see Equation (1))                                          |
| log_M BH_err         | DOUBLE  | M☉           | Uncertainty of log_M BH                                                    |
| log_Lbol             | DOUBLE  | erg s⁻¹       | Bolometric luminosity (see Section 2.4)                                     |
| log_Lbol_err         | DOUBLE  | erg s⁻¹       | Uncertainty of log_Lbol                                                    |
| log_lambdal_Edd      | DOUBLE  |               | Eddington ratio                                                            |
| log_lambdal_Edd_err  | DOUBLE  |               | Uncertainty of log_lambdal_Edd                                             |
| rechi2_XCIGALE       | DOUBLE  |               | Reduced $\chi^2$ derived from X-CIGALE                                       |
| Delta_BIC            | DOUBLE  |               | BICwpolar−BICwpolar (see Section 3.1)                                       |
| E_BV                 | DOUBLE  | mag           | Color excess ($EB - V$) derived from X-CIGALE                               |
| E_BV_err             | DOUBLE  | mag           | Uncertainty of E_BV derived from X-CIGALE                                   |
| log_M                | DOUBLE  | M☉           | Stellar mass derived from X-CIGALE                                          |
| log_M_err            | DOUBLE  | M☉           | Uncertainty of log_M derived from X-CIGALE                                  |
| log_SFR              | DOUBLE  | M☉ yr⁻¹       | SFR derived from X-CIGALE                                                   |
| log_SFR_err          | DOUBLE  | M☉ yr⁻¹       | Uncertainty of SFR derived from X-CIGALE                                    |
| log_LIR              | DOUBLE  | $L_\odot$     | IR luminosity derived from X-CIGALE                                         |
| log_LIR_err          | DOUBLE  | $L_\odot$     | Uncertainty of log_LIR derived from X-CIGALE                                 |
| log_LIR_AGN          | DOUBLE  | $L_\odot$     | IR luminosity contributed from AGN derived from X-CIGALE                   |
| log_LIR_AGN_err      | DOUBLE  | $L_\odot$     | Uncertainty of log_LIR_AGN derived from X-CIGALE                             |
| log_LIR_AGN_polar    | DOUBLE  | erg s⁻¹       | IR luminosity contributed from AGN polar dust component derived from X-CIGALE |
| log_LIR_AGN_polar_err| DOUBLE  | erg s⁻¹       | Uncertainty of log_LIR_polar derived from X-CIGALE                          |
| CF_AGN_torus         | DOUBLE  |               | Covering factor of AGN dust torus (see Equation (2))                         |
| CF_AGN_torus_err     | DOUBLE  |               | Uncertainty of CF_AGN_torus                                                 |

Note. A total of 5752 quasars with $(\chi^2/\text{dof})_{\text{qsfs}} < 3.0$, $(\chi^2/\text{dof})_{\text{XCIGALE}} < 3.0$, $\Delta \text{BIC} > 6$, Cont$_{5100, \text{Qual}} = 0$, and HB BR Qual = 0 are used for a correlation analysis (see Section 3.3).

(This table is available in its entirety in FITS format.)

ORCID iDs

Yoshiki Toba 🏙️ https://orcid.org/0000-0002-3531-7863
Yoshishiro Ueda 🏙️ https://orcid.org/0000-0001-7821-6715
Poshak Gandhi 🏙️ https://orcid.org/0000-0003-3105-2615
Claudio Ricci 🏙️ https://orcid.org/0000-0001-5231-2645
Denis Burgarella 🏙️ https://orcid.org/0000-0002-4193-2539
Veronique Buat 🏙️ https://orcid.org/0000-0003-3441-903X
Tohru Nagao 🏙️ https://orcid.org/0000-0002-7402-5441
Shinki Oyabu 🏙️ https://orcid.org/0000-0003-4842-565X
Bau-Ching Hsieh 🏙️ https://orcid.org/0000-0001-5615-4904

References

Aihara, H., Allende Prieto, C., An, D., et al. 2011, ApJS, 193, 29
Alonso-Herrero, A., Ramos Almeida, C., Mason, R., et al. 2011, ApJ, 736, 82
Antonucci, R. 1993, ARA&A, 31, 473
Asmus, D. 2019, MNRAS, 489, 2177
Auftor, G., Ciesla, I., Padlo, P., & Buat, V. 2020, A&A, 635, A136
Baba, S., Nakagawa, T., Isobe, N., & Shirahata, M. 2018, ApJ, 852, 83
Baes, M., Verstappen, J., de Looze, I., et al. 2011, ApJS, 196, 22
Balaković, M., Brightman, M., Harrison, F. A., et al. 2018, ApJ, 854, 42
Bolton, A. S., Schlegel, D. J., Aubourg, E., et al. 2012, AJ, 144, 144
Boquien, M., Buat, V., & Perret, V. 2014, A&A, 571, A72
Boquien, M., Burgarella, D., Roehlly, Y., et al. 2019, A&A, 622, A103
Boquien, M., Kennicutt, R., Calzetti, D., et al. 2016, A&A, 591, A6
Bruzual, G., & Charlot, S. 2003, MNRAS, 344, 1000
Buat, V., Ciesla, I., Boquien, M., Malek, K., & Burgarella, D. 2019, A&A, 632, A79
Buat, V., Heinis, S., Boquien, M., et al. 2014, A&A, 561, A39
Buat, V., Noll, S., Burgarella, D., et al. 2012, A&A, 545, A141
Buat, V., Oi, N., Heinis, S., et al. 2015, A&A, 577, A141
Burgarella, D., Buat, V., & Iglesias-Páramo, J. 2005, MNRAS, 360, 1413
Burgarella, D., Nanni, A., Hirashita, H., et al. 2020, A&A, 637, A32
Burlon, D., Ajello, M., Greiner, J., et al. 2011, ApJ, 728, 58
Calderone, G., Nistico, L., Ghisellini, G., et al. 2017, MNRAS, 472, 4051
Camps, P., & Baes, M. 2015, A&C, 9, 20
Cao, X. 2005, ApJ, 619, 86
Casey, C. M. 2012, MNRAS, 425, 3094
Charbrier, G. 2003, PASP, 115, 763
Charlot, S., & Fall, S. M. 2000, ApJ, 539, 718
Ciesla, L., Boselli, A., Elbaz, D., et al. 2016, A&A, 585, A43
Ciesla, L., Charmandaris, V., Georgakakis, A., et al. 2015, A&A, 576, A10
Ciesla, L., Elbaz, D., & Fensch, J. 2017, A&A, 608, A41
Ciesla, L., Elbaz, D., Schreiber, C., Daddi, E., & Wang, T. 2018, A&A, 615, A61
Cutri, R. M., Wright, E. L., Conrow, T., et al. 2014, yCat, 2328, 0
Dietrich, M., Appenzeller, I., Vestergaard, M., & Wagner, S. J. 2002, ApJ, 564, 581

(See Table 4 in the original document.)
