We define $L_{\lambda} = L_{\lambda}(\mu m) = 4\pi d_L^2 \lambda F_\lambda$ as the rest-frame monochromatic luminosity, where $d_L$ is the luminosity distance and $F_\lambda$ is the rest-frame specific flux.

1 Throughout this paper, we use the term “dust-poor” to indicate weak IR emission. Throughout this paper, we use the term “dust-poor” to indicate weak IR emission.
of the SED becomes meaningful, it would be better to use dust emission strength indicators that take into account the fraction of host galaxy light (H10), or to apply a luminosity-dependent average galaxy contamination correction to the observed fluxes (e.g., Shen et al. 2011, hereafter S11). Moreover, selection of hot dust-poor quasars to date has relied on the weak NIR emission, and it is unclear whether hot dust-poor quasars are also dust-poor in warmer phases, where the mid-infrared (MIR) is thought to be the peak wavelength of AGN dust emission (e.g., Richards et al. 2006). Finally, all previous studies lack either the sample size (J10; H10) or redshift coverage (M11; Ma & Wang 2013) to meaningfully disentangle number evolution and characteristics of the physical parameters of dust-poor quasars.

In this paper, we aim to identify the lower redshift counterparts of the high-redshift, hot dust-poor quasars of J10, to compare and understand the observational features of local with high-redshift populations. Where our sample quasars are defined to be luminous enough to have almost negligible host contamination (Section 2), we choose NIR to optical flux ratios to find weak hot dust emission sources matching those in J10. Our spectrophotometric data (Section 2), encompassing 41,000 quasars at $0 < z < 5$ with contiguous wavelength coverage from the UV to the IR, enables reliable modeling of the SED and measurement of both hot and warm dust emission strengths (Section 3). With the help of large number statistics and multi-wavelength data, we are able to better identify dust-poor quasars, constrain their evolution in redshift space, and understand their nature as reflected through key physical parameters (Sections 4 and 5). Throughout, we adopt a flat $\Lambda$CDM cosmology with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$.

2. SAMPLE DEFINITION AND AGN DATA SET

For the selection of hot dust-poor quasars, we follow J10 and use NIR to optical flux ratios to indicate the relative strength of the dust emission. Defining $f_\alpha$ as the $\lambda$ $\mu$m to optical flux ratio, we categorize “hot dust-poor” quasars as those with $f_{2.3} < -0.5$, where $f_{2.3}$ is chosen for the 2.3 $\mu$m data to be effective in constraining the hot dust emission, as it is the wavelength where the 1250 K blackbody component for the SED fitting (Section 3) peaks in $F_\lambda$-space. In addition, the hot dust-poor criterion is set to select objects with a weak NIR bump at 2.3 $\mu$m, equivalent to objects from J10 that are below the lower 3$\sigma$ distribution in $f_{3.5}$ ($f_{3.5} < -0.5$). In Figure 1, our selection criterion is compared with the SEDs of quasars from J10. Because of the variety of quasar optical continuum slopes, a single value of $f_{2.3}$ can be derived from a range of $\alpha$, where $F_\nu \propto \nu^{\alpha}$. In this figure, we show two example SEDs with different continuum slopes that satisfy $f_{2.3} = -0.5$, with $\alpha$ lying within 1$\sigma$ of the average of all quasars in this work. If $\alpha = -0.24$, the SED is purely a power law in the optical–NIR (black solid line); when $\alpha = 0.10$, the SED is the sum of a power law and a weak hot dust emission component similar in strength to that of J11/1+1217 from J10 (dashed line). The $f_{3.5}$ for both examples are $-0.64$ and $-0.57$, which are higher than $f_{3.5} \lesssim -1$ for the two hot dust-free quasars in J10 but still below the lower 3$\sigma$ range of $f_{3.5}$ in Figure 2 of J10, separating weak hot dust-radiating AGNs from the rest of the distribution.

3 We use rest-frame flux for $F_\lambda$, $F_{\mu}$ throughout the paper, in uppercase to prevent confusion with the rest-frame flux ratio $f_\alpha$.
multiple matching than for SDSS–UKIDSS at an identical 2" matching radius. For this reason, we did not reject the multiple SDSS–2MASS matched objects without UKIDSS coverage in principle but visually reexamined the SDSS images of the vicinity of hot dust-poor quasars (Section 4.1) to remove those with definite source confusion within the angular resolution of the SDSS imaging. Meanwhile, hot dust-rich \((f_\text{z} > -0.5)\) objects without UKIDSS data are revealed to have a mild level of confusion, expected to be 0.72% from the SDSS–UKIDSS matching, although we regard this fraction to be negligible in counting the number of hot dust-rich quasars later on. Finally, objects undetected or blended in \textit{WISE} are given with upper flux limits, while those undetected in the NIR were removed, in order to provide careful constraints on the dust emission strength.

Photometric data collected from multiwavelength catalogs can potentially suffer from several problems: First, the photometry of AGNs includes contributions from the host galaxy that needs to be minimized or subtracted somehow. Second, the mixture of different definitions of Kron, point-spread function (PSF), aperture, and profile-fit magnitudes for UV, optical, NIR, and MIR data brings in inaccurate photometry of extended objects from PSF or aperture magnitudes. Both of these potential problems can be avoided by minimizing the host galaxy contamination. Thus, we limited our sample with a bolometric luminosity cut of \(L_{\text{bol}} > 10^{45.70}\) erg s\(^{-1}\), derived from \(L_{\text{bol}} > 10^{44.73}\) erg s\(^{-1}\) (Section 3) using an optical-to-bolometric correction of 9.26 (S11). By doing so, host contamination is limited to less than 10% in 5100 Å (S11). After applying the luminosity cut, we double-checked whether fixed-aperture (PSF or aperture) magnitudes were consistent with total magnitudes by comparing PSF versus Petrosian magnitudes for the SDSS \(ugriz\) filters, and aperture versus Petrosian magnitudes for 2MASS or UKIDSS \(JHK\) filters. We found the median difference between the magnitude systems to be at most 0.03 mag at all filters, with the rms scatter falling within 0.1 mag for SDSS or UKIDSS data and within 0.2 mag for 2MASS. Therefore, we consider our luminosity-cut sample to have a compatible set of magnitudes dominated by the central AGN contribution.

As a next step, we imposed an \(i\)-band flux limit that varies with redshift and the \textit{WISE} depth for each object. This is necessary because the \textit{WISE} flux limits are not deep enough for some of the SDSS quasars to determine whether the object has \(f_\text{z} > -0.5\). In other words, we selected objects that are bright enough in both observed-frame \(i\) and \textit{WISE} bands to allow us to determine whether the object is dust-poor or not. Since each observed band traces different rest-frame wavelengths at different redshifts, the \(i\)-band cut changes as a function of redshift. Furthermore, the \textit{WISE} depths are not uniform over the entire sky, so the \(i\)-band depth needs to be different at each location on the sky. The \(i\)-band flux limits were determined by requiring a quasar with \(f_\text{z} = -0.5\) at the \(i\)-band magnitude to have a 2σ detection in the \textit{WISE} band covering rest-frame 2.3 μm. Figure 2(a) shows a fiducial \(i\)-band magnitude limit, which assumes the typical \textit{WISE} limit with 97 s exposure (11 frames; Wright et al. 2010). When the exposure time, \(t_{\exp}\), was different at the position of another quasar, we adjusted the fiducial \(i\)-band limit by adding 1.25 \(\log(t_{\exp}/97\) s). The objects passing the \(i\)-band limit are depicted in Figure 2(b).

Last, we required at least two data points to lie in the rest-frame 0.3–1 μm with one of the points shortward of 0.6 μm, so that the optical continuum slope could be reliably measured from the SED fitting. In short, going over the number of matches through the sample selection process, 100% and 54% of SDSS quasars have NIR coverage and detection, respectively, where almost all the nondetections come from the shallow 2MASS data. From the NIR-detected data 100% and 91% are covered and detected in the \textit{WISE} MIR, yielding 49% of the initial catalog to be matched with contiguous rest-frame UV–NIR information, of which 82% are matched in the \textit{GALEX} UV. The bolometric luminosity cut passes through 81% of the multiwavelength data, while the \(i\)-band limit leaves a further 56% of the remaining sample. Finally, the constraints on the shallow \textit{WISE} upper limits and the number of optical data points sum to a 2% rejection, leaving 22% of the initial SDSS sample, or 40,825 objects, for the SED fitting analysis. We summarize the final data set and observations in Table 1.

### 3. FITTING OF BROADBAND SEDS AND SPECTRA

We modeled individual quasar SEDs within rest-frame 0.3–20 μm boundaries as a combination of a power-law continuum from the accretion disk and blackbody emission from heated dust in hot and warm phases. For all quasars, a default dust spectrum describes the NIR part of the SED (Glikman et al. 2006). In cases where rest-frame 3.5 and 9 μm data were available, 500 and 200 K blackbodies were added respectively to model the MIR continuum emission of AGNs through warm dust phases, where the combination of warm dust temperatures is found to fit the observed SEDs of AGNs well (e.g., Barvainis 1987; Hao et al. 2005). Quantitatively expressing the model SED as

\[
F_\lambda = F_\lambda,\text{disk} + F_\lambda,\text{dust},
\]

it consists of an accretion disk component \(F_\lambda,\text{disk} = c_{\text{disk}} \lambda^{-2(α+1)}\) and a combination of dust emission components \(F_\lambda,\text{dust} = c_{\text{id}} B_{\text{id}}(12500\) K) + \(c_{\text{wd}} B_{\text{wd}}(2000\) K), where \(α\) is the power-law continuum slope in \(F_\nu\) \(∝\nu^α\) and \(c_{\text{id}}, c_{\text{wd}},\) and \(c_{\text{wd}}\) are contributions from the hot (1250 K), intermediate (500 K), and warm (200 K) dust blackbodies. The \(c_{\text{id}}\) and \(c_{\text{wd}}\) were used when the rest-frame IR data included 3.5 μm/9 μm, the geometric mean of the peak wavelengths out of hot–intermediate/intermediate–warm components, and were fixed to zero otherwise. The peaks of the blackbody radiation from hot- and warm-dust models in \(F_\lambda\)-space are at 2.3 and 14 μm, which means that \textit{WISE} covers hot dust emission mostly within the W1–W3 bands over \(z = 0–4\), while warm dust emission is usually probed under the inclusion of W4 at \(z < 0.5\).
The SED fitting was performed over the entire sample of 40,825 objects, which excludes 139 and 895 quasars that were rejected (Section 2) because of shallow WISe upper limits and insufficient rest-frame optical coverage, respectively. The median reduced chi-squared values, \( \chi^2 \), are not the best, at 5.4 and 3.0, for all and for hot dust-poor objects separately. Still, we find the high-\( \chi^2 \) sources (e.g., in Figure 5) to show acceptable fits to the data, while there are no cases without a fit solution in the entire sample. Rather large \( \chi^2 \)-values do not indicate a poor determination of the continuum slope, since they are caused by wiggly features in the continuum such as broad emission lines or the Fe II complex and photometric variabilities between different-wavelength data sets. A further test of the accuracy of the SED fitting under special conditions, when the gap between the WISe W2 and W3 bands becomes problematic in constraining the \( f_{2.3} \), is described in Section 4.2.

Having gone through the SED fitting, we used IR to optical flux ratios \( f_{2.3} \) and \( f_{10} \) to quantify hot/warm dust emission strengths over that of the optical continuum. We measured \( f_{2.3} \) and \( f_{10} \) from the fluxes on the fitted SED curve at the corresponding rest-frame wavelengths, while \( f_{10} \) was computed only when the warm (200 K) dust component was used for the SED fit. Upper limits for \( f_{2.3} \) and \( f_{10} \) were provided from the upper flux limits in the case of WISe nondetections, taking the upper flux limits as detections. The use of \( f_{2.3} \) and \( f_{10} \) instead of \( \alpha_{C, \text{disk}}, \alpha_{C, \text{dust}}, \alpha_{\text{dust}}, \) and \( \alpha_{wd} \) is more straightforward for selecting quasars with weak dust emission, as \( \alpha_{C, \text{dust}}, \alpha_{\text{dust}}, \) and \( \alpha_{wd} \) are easily coupled with \( \alpha \), which varies by object. An example is a red quasar with low \( \alpha \) due to optical extinction and high \( f_{2.3} \) and \( f_{10} \) from strong hot/warm dust emission. Because the extrapolated red power-law component could take care of the NIR–MIR emission, the resultant small \( \alpha_{C, \text{dust}}, \alpha_{\text{dust}}, \) and \( \alpha_{wd} \), for instance, are not necessarily good indicators of little dust emission.

We wanted to pay careful attention for the modeling to be robust against systematic effects. First, broad emission lines could disturb the optical broadband fluxes from a simple power-law continuum model, where \( H\alpha \) is the strongest and the only meaningful (>0.02 dex) line contamination within our wavelength of interest (Hao et al. 2011). Therefore, we removed the broadband point enclosing rest-frame \( H\alpha \) if the \( \chi^2 \) containing that data point was larger than that without. We additionally note that although the rest-frame 10 \( \mu \)m is often surrounded by polycyclic aromatic hydrocarbon emission and silicate absorption features, we expect the line contamination to be negligible considering the very wide filter transmission of W3 and W4. Second, variability can be a problem with multiwavelength data taken at different epochs, because it could bring flux offsets. As a sanity check, we computed the scatter in the magnitude difference between the 2MASS and UKIDSS J and KAB magnitudes, finding the median rms of the magnitude difference to be \( \sim 0.1 \) mag after subtracting the magnitude measurement error in quadrature. Because this level of variability is limited, and indistinguishable from that derived from hot dust-poor quasars alone, we consider the variability issue to be tolerable for the selection of hot dust-poor SEDs.

To supplement the photometric products with spectroscopy, we compiled black hole masses based on the UV/optical line and continuum fitting (of both DR7 and DR9 data) by S11, adopting \( M_{\text{BH}} \) estimators in the form

\[
\log \left( \frac{M_{\text{BH}}}{M_\odot} \right) = a + b \log \left( \frac{L_\lambda}{10^{44} \text{ erg s}^{-1}} \right) + c \log \left( \frac{\text{FWHM}}{10^3 \text{ km s}^{-1}} \right) \ ,
\]

with \( L_\lambda = (L_{0.51}, L_{0.51}, L_{0.135}) \) and \( (a, b, c) = ((6.69, 0.50, 2.1), (6.91, 0.50, 2), (6.66, 0.53, 2)) \), for spectral regions around \( H\alpha, H\beta, \) and \( C\ IV \), respectively. For the \( Mg\ II \) estimator, \( L_\lambda = L_{0.3} \) and \( (b, c) = (0.62, 2) \), while \( a = (6.75, 6.81, 6.79) \) depending on the narrow line to be subtracted or included (DR7), or unused in the fitting (DR9), individually. The \( H\alpha, H\beta, Mg\ II, \) and \( C\ IV \) recipes were originally from Greene & Ho (2005), Vestergaard & Peterson (2006), McLure & Dunlop (2004), and Vestergaard & Peterson (2006), respectively, but we primarily followed the cross-calibrated form of \( (a, b) \) from S11 to provide consistency between \( M_{\text{BH}} \) from different lines. Within the following redshift intervals, we used the black hole mass estimator from \( H\alpha \) \((z < 0.37)\), \( H\beta \) \((z < 0.84)\), \( Mg\ II \) \((0.7 < z < 2.1)\), and \( C\ IV \) \((z > 2.1)\), while masses from different estimators were averaged for overlapping redshifts.

Because of the automatic nature of the spectral fitting in S11, we visually inspected the fits for hot dust-poor quasars as a sanity check, tried direct fitting by ourselves, and compared with the
M$_{BH}$ in S11 from different methodologies. The continuum and line fits by S11 were reproducible overall, but with cases of problematic fitted results. First of all, we checked the H$\beta$ fits by following the method of S11 except for using the Fe II template of Tsuzuki et al. (2006) to fit the spectra around the H$\beta$ region. For a total of nine quasars at $z < 0.84$, we found good agreement in our H$\beta$ M$_{BH}$ with S11 values, with $-0.09 \pm 0.08$ dex relative offset and scatter. Thus, we trust and keep the H$\beta$ M$_{BH}$ of S11. Likewise, we performed C IV fits for 92 hot dust-poor quasars at $z > 2.1$ with similar methodology to S11, but carefully masking out the absorption features. We found 20 spectra with strong absorption, including broad absorption line (BAL) systems, such that the fitting would be meaningless. Hence, for the spectra with severe C IV absorption but good quality in C III$\lambda$ 1908 (see, e.g., Figure 3), we fitted C III$\lambda$ 1908 as an effective surrogate for the C IV full width at half-maximum (FWHM) (Shen & Liu 2012) for nine objects, while we dropped the M$_{BH}$ for the remaining 11 objects. The C IV M$_{BH}$ without absorption spectra are offset by $-0.05 \pm 0.22$ dex relative to S11’s values, where we keep our C IV– and C III$\lambda$–based M$_{BH}$ for the better treatment of absorption features.

For the Mg II fitting, we note that the DR7 and DR9 spectra are treated differently in S11, such that the DR7 broad Mg II FWHMs are measured with and without subtracting the narrow ($<1200 \text{ km s}^{-1}$) component whereas the narrow-line component itself is not used for the DR9 fitting. In order to shift each Mg II mass estimator to be mutually consistent, we followed the argument of S11 to normalize each Mg II M$_{BH}$ to the H$\beta$ M$_{BH}$ of Vestergaard & Peterson (2006), obtaining the coefficient $a$ in Equation (3), while keeping $b$ and $c$ fixed. This process was performed for all 2489 objects covering both H$\beta$ and Mg II emission lines at $0.7 < z < 0.8$ with continuum S/N $> 5$. We find $a = 6.75$ when using the Mg II line width measured when subtracting the narrow component, consistent with 6.74 in S11, and $a = 6.81$ when the narrow component is included. Next, we normalized the DR9 Mg II M$_{BH}$ with that of 1125 overlapping DR7 objects at $0.7 < z < 2.1$ to find $a = 6.79$, irrespective of whether the narrow Mg II lines of DR7 quasars are subtracted or not, and even when these two DR7 masses are averaged. Since it is still debatable whether the narrow component should be subtracted for the Mg II line width measurement (e.g., S11), we averaged the M$_{BH}$’s with the narrow component subtracted or included for the DR7 sample that gave the least scatter with the overlapping DR9 M$_{BH}$; at the same time, caution regarding the accuracy of S11’s Mg II M$_{BH}$’s is called for until the fitting-dependent systematic uncertainties are clarified in the future.

Last, we replaced seven Mg II M$_{BH}$’s at $z < 2.1$ with low S/N with those from C IV.

In addition to the black hole mass estimates, we computed the bolometric luminosities from the 5100 Å monochromatic luminosity, $L_{5100}$, derived from our own broadband SED fit. This approach may reduce the systematic uncertainties from extinction or BAL features compared with converting the rest-frame UV into bolometric luminosity. We used a constant bolometric correction of 9.26 (S11), derived from the composite quasar SED of Richards et al. (2006). To check whether our photometrically determined 5100 Å luminosities are reliable, we compared our values with that from the spectral fitting in S11, finding good agreement, with a difference $L_{5100} - L_{5100, S11} = 0.06 \pm 0.16$ dex.

4. RESULTS

4.1. Number Counts and SEDs of Dust-poor Quasars

There are 253 objects that met the hot dust-poor quasar criterion $f_{2.3} < -0.5$. By visually inspecting individual images and spectra, we find 17 blended images in SDSS and three stellar spectra, which are rejected. After all this, we keep 233 hot dust-poor quasars from a total of 40,805, or 0.6%. Figure 4 shows the composite SED of hot dust-poor quasars together with that of the whole sample. Both composites were constructed by the geometric mean so as to preserve the global continuum shape (Vanden Berk et al. 2001), after normalizing individual SEDs at 0.51 $\mu$m. We fitted the composite SEDs with third-order polynomials in the UV ($<0.3 \mu$m) and with optical power-law plus IR blackbody combinations (Section 3) to obtain the overall shape information, and to compare the bolometric corrections (Section 4.2). The composite hot dust-poor SED in Figure 4 is bluer in the optical, and about three times fainter in the rest-frame 2.3 $\mu$m, than the composite of all SEDs.
Figure 5. Selected list of hot dust-poor quasar SEDs, sorted by redshift. Along with the observed data points and 2σ upper limits, model fits with an accretion disk (blue) and dust components with $T = 1250, 500, \text{ and } 200 \text{ K}$ phases (red) are overplotted. We include the 500 and 200 K blackbodies only when the longest wavelength of each SED exceeds 3.5 and 9 $\mu$m, respectively, except for calculating upper limits in $f_{2.3}/f_{10}$. In addition, the composite SED of luminous ($L_{\text{bol}} \gtrsim 10^{46} \text{ erg s}^{-1}$) SDSS quasars (gray; Richards et al. 2006) normalized to the data at 5100 Å are overplotted. SDSS J144706.80+212839.3, at $z = 3.23$ (bottom, second from left), is the quasar with the smallest NIR to optical flux ratio, $f_{2.3}/f_{10} = -0.88$, reaching down to values similar to J10’s dust-free quasars.

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

| Name                        | $z$   | $f_{2.3}$ | $f_{10}$ | log $L_{\text{bol}}$ | log $M_{\text{BH}}$ | $f_{\text{Edd}}$ |
|-----------------------------|-------|-----------|----------|-----------------------|----------------------|------------------|
| J001754.17+011123.4         | 1.465 | -0.77     | 99.00    | 46.503 ± 0.020        | 8.47 ± 0.32         | 0.836 ± 0.609   |
| J005205.56+003538.2         | 0.399 | -0.52     | -0.48    | 46.521 ± 0.004        | 8.43 ± 0.01         | 0.959 ± 0.030   |
| J012112.14–003037.1         | 1.654 | -0.64     | 99.00    | 46.594 ± 0.020        | 8.75 ± 0.07         | 0.532 ± 0.088   |
| J013113.4–093401.1         | 1.149 | -0.53     | -0.43    | 46.759 ± 0.027        | 9.18 ± 0.08         | 0.293 ± 0.058   |
| J014036.47+000335.9         | 1.636 | -0.58     | 99.00    | 46.975 ± 0.011        | 10.09 ± 0.03        | 0.059 ± 0.005   |

Notes. Catalog of hot dust-poor quasars sorted by right ascension, where only the first five rows are displayed. The units for $L_{\text{bol}}$ and $M_{\text{BH}}$ are erg s$^{-1}$ and $M_\odot$, respectively. Empty values are entered as 99.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

Individual hot dust-poor SEDs overplotted with the composite in Figure 4 are also depicted with model fits in Figure 5, while their properties are summarized in Table 2. We find that the majority of hot dust-poor quasars exhibit warm dust emission under the detection of NIR–MIR, even if the hot dust component is negligible. Exceptions are objects for which upper limits in the rest-frame MIR do not allow us to assess whether they are lacking a warm dust component or not. Specifically, the optical–NIR spectral shapes of the upper W4 limit objects at $z > 2$ in Figure 5 are similar to the two dust-free quasars in J10. Nevertheless, we would like to be careful about calling these objects “dust-free,” instead using the term “dust-poor” until deep MIR data are available to confirm the absence of warm dust emission. Although mostly present in warm dust emission, our hot dust-poor quasars are in general very weak in hot dust emission that would belong to a smaller subset of hot dust-poor AGNs in other studies. Our hot dust-poor quasars fall within H10’s class II, i.e., hot dust-poor quasars that are power-law shaped in the optical–NIR, or optically blue hot dust-poor quasars in M11.

To better understand the photometric properties of hot dust-poor quasars, we plot the luminosity correlations in Figure 6. The NIR versus optical luminosities in Figure 6(a) show that $L_{2.3}$ is in general proportional to $L_{51}$, meaning luminous AGNs show stronger dust emission than faint AGNs (see, e.g., Haas et al. 2003). With respect to this relation, we find that hot dust-poor quasars are the objects defining the lower $\sim 3.2\sigma$ envelope. Next, warm and hot dust emission strengths are compared through the 2.3 $\mu$m versus 10 $\mu$m luminosities in Figure 6(b), which shows a linear relation between the MIR and NIR luminosities. Interestingly, the detected hot dust-poor data points lie moderately below the relation, by $1.8\sigma$ on average, suggesting perhaps a shifted MIR–NIR luminosity relation for hot dust-poor SEDs. Nonetheless, we may find hot dust-poor

---

Table 2

| Name                        | $z$   | $f_{2.3}$ | $f_{10}$ | log $L_{\text{bol}}$ | log $M_{\text{BH}}$ | $f_{\text{Edd}}$ |
|-----------------------------|-------|-----------|----------|-----------------------|----------------------|------------------|
| J001754.17+011123.4         | 1.465 | -0.77     | 99.00    | 46.503 ± 0.020        | 8.47 ± 0.32         | 0.836 ± 0.609   |
| J005205.56+003538.2         | 0.399 | -0.52     | -0.48    | 46.521 ± 0.004        | 8.43 ± 0.01         | 0.959 ± 0.030   |
| J012112.14–003037.1         | 1.654 | -0.64     | 99.00    | 46.594 ± 0.020        | 8.75 ± 0.07         | 0.532 ± 0.088   |
| J013113.4–093401.1         | 1.149 | -0.53     | -0.43    | 46.759 ± 0.027        | 9.18 ± 0.08         | 0.293 ± 0.058   |
| J014036.47+000335.9         | 1.636 | -0.58     | 99.00    | 46.975 ± 0.011        | 10.09 ± 0.03        | 0.059 ± 0.005   |
rms = line just above the gray highlighted line are SEDs fitted as pure power laws for the entire and the dust-poor samples. The data points forming the diagonal line in Figure 6. The average and standard deviation of the luminosities of quasars (e.g., Haas et al. 2003), further suggest the acceptable correlation between MIR and far-IR (FIR) detections. Therefore, we find it reasonable from our NIR luminosities to deduce that hot dust emission is a marginally possible offset, to deduce that hot dust-poor sources stay relatively dust-poor through the red end of small $\alpha$. Therefore, we regard at least part of the diagonal sequence in Figure 7 to effectively represent lower limits in the measured $\alpha$.

In addition to the optical continuum slope measurements from photometric data points, we constructed a composite UV–optical spectrum of dust-poor quasars, plotted in Figure 8(a), along with the composite of general SDSS quasars from Vanden Berk et al. (2001). Compared with typical quasars, dust-poor quasars have a bluer NUV–optical continuum slope. Moreover, fitting all prominent UV–optical emission lines, we find the He II $\lambda$4686 line emission of dust-poor quasars to be especially strong, with equivalent widths that are about 1.7 times higher than measured using the composite from Vanden Berk et al. (2001), in Figure 8(b). For the He II fitting, we subtracted the continuum and broad Fe II in a similar way as S11 but with the template of Tsuzuki et al. (2006), while a single Gaussian profile was used for both broad and narrow emission components of He II. The He II region was simultaneously fitted with H$\beta$ and [O III] lines to better decompose the He II line emission. Because He II $\lambda$4686 is relatively well decoupled from neighboring emission lines, and to check whether the strong He II of the dust-poor composite spectrum is reflected in the individual spectra, we further calculated the He II/H$\beta$ line ratios for all quasars to stay on the warm dust-poor side, as their 10 $\mu$m luminosities are lower by 1.9$\sigma$ on average than the linear relation, $\log L_{10} = (1.148 \pm 0.004) \log L_{0.51} - (6.627 \pm 0.188)$, $\text{rms} = 0.200$, derived from the entire sample with 10 $\mu$m detections. Therefore, we find it reasonable from our NIR/MIR luminosity correlation of hot dust-poor quasars, although with a possible offset, to deduce that hot dust emission is a marginally good tracer of warm dust emission in AGNs. The IR portion of the quasar SED peaking in the MIR (e.g., Richards et al. 2006), and the acceptable correlation between MIR and far-IR (FIR) luminosities of quasars (e.g., Haas et al. 2003), further suggest that hot dust-poor sources stay relatively dust-poor through the entire IR. For these reasons, we choose to refer to “hot dust-poor” quasars as “dust-poor” quasars from here on.

To investigate how dust-poor quasars differ from ordinary quasars in wavelengths other than the NIR/MIR, we plot $f_{2.3}$ as a function of optical continuum slope $\alpha$ in Figure 7. The average slope and its scatter, $\langle \alpha \rangle = -0.08 \pm 0.31$, from our entire sample are somewhat bluer than the $-0.44$ of Vanden Berk et al. (2001). This is consistent with the results of Davis et al. (2007), where more luminous quasars have bluer continuum slopes, as our sample are high-luminosity-selected SDSS quasars. We also note that differences in the fitting range or the method to measure $\alpha$ could further shift the values of $\alpha$ (see, e.g., Table 5 of Vanden Berk et al. 2001). In any case, $\langle \alpha \rangle = 0.10 \pm 0.20$ for dust-poor quasars comes roughly close to the $\alpha = (1/3)$ predicted from optically thick and locally heated accretion disk models, and from polarized observations of quasar SEDs seen through the dust (Kishimoto et al. 2008). This indicates that the optical continua from the accretion disks of dust-poor quasars are mostly unobscured to our line of sight, consistent with the weak IR reemission observed. Meanwhile, there are points forming a diagonal line across the lower left part of $\alpha$–$f_{2.3}$ space in Figure 7, which are optical to NIR SEDs best fitted by the continuum component only. Although these objects do not seem to involve a hot dust component for the SED fitting, satisfying $\chi^2_{\text{dust}} = 0$ in Equation (2), the NIR emission could be taken over by the extrapolated optical continuum component, especially at the red end of small $\alpha$. Therefore, we regard at least part of the diagonal sequence in Figure 7 to effectively represent lower limits in the measured $\alpha$.

Figure 6. Correlations between (a) optical and NIR monochromatic luminosities and (b) MIR and NIR luminosities. The distributions of hot dust-poor quasars (purple; filled circles represent detections, and open arrows are based on WISE 2$\sigma$ upper limits at the corresponding wavelengths) and of the rest of the sample (dots; detections only) are plotted, together with an overall median error bar at upper left in each panel. Linear fits to luminosity correlations are obtained by applying the ordinary least-squares bisector method (Isobe et al. 1990) to the entire sample with detections; the fit coefficients and rms scatter are shown. (A color version of this figure is available in the online journal.)

Figure 7. Distribution of $f_{2.3}$ with continuum slope $\alpha$, following the styles in Figure 6. The average and standard deviation of $\alpha$ are displayed for both the entire and the dust-poor samples. The data points forming the diagonal line just above the gray highlighted line are SEDs fitted as pure power laws in the optical–NIR, with no contribution from a hot dust component ($c_{\text{dust}} = 0$). The gray shaded regions are prohibited, since they require $c_{\text{dust}} < 0$.

(A color version of this figure is available in the online journal.)
Figure 8. (a) Composite spectra of dust-poor quasars (purple) and of general SDSS quasars (black; from Vanden Berk et al. 2001), smoothed by 3 pixels to display the spectral features better. The numbers of spectra used to construct the composite, from top to bottom, are 163, 125, and 22 for dust-poor quasars and around 500, 1800, and 700 from Vanden Berk et al. (2001). (b) Spectral fits around the Hβ region for dust-poor (top) and ordinary (bottom) composites. The measured He II λ4686 equivalent widths are shown for both samples.

Figure 9. Distribution of He II λ4686 to Hβ broad-line fluxes, following the styles of Figure 6. The Hβ and He II λ4686 line fluxes are measured for objects at z < 0.8, with an overall median error bar shown at upper left. Of 3880 continuum S/N > 10 spectra, 1899 have nondetections in Hγ or He I or fail to have an Hβ line S/N > 2, where they are excluded from the plot. The average and standard deviation of He II/ Hβ are shown for both the entire and the dust-poor samples.

\[ \frac{L_{\text{He II} \lambda 4686}}{L_{\text{H} \beta}} = 1.99 \times 4^{\alpha_{\text{EUV}}} \]  

(Penston & Fosbury 1978), where \( \alpha_{\text{EUV}} \) indicates the EUV slope of the source that brings H I and He II emission. Equation (4) yields a bluer slope of \( \alpha_{\text{EUV}} \sim -2.0 \) for dust-poor quasars, which hints at their broad-line regions’ being more illuminated by energetic UV photons than average, consistent with the observed bluer EUV spectra in the left part of the top panel of Figure 8(a). This, together with the blue NUV–optical spectra of dust-poor quasars in Figure 8(a), suggests that high-temperature, energetic radiation sources are connected to the dust-poor property. An example of such a case would be the model prediction of an accretion disk temperature–dependent UV–optical color for AGNs (Bonning et al. 2007).

4.2. Parameter Space Study of Dust-poor Quasars

Figure 10 shows the distribution of AGNs in our sample in \( L_{\text{bol}} \) versus redshift, and \( f_{\text{Edd}} \) versus \( M_{\text{BH}} \). Also plotted are the range of parameter space covered by other studies (H10 and M11). Here the dashed boundary for the M11 sample is determined following their selection criteria, and we mimic the distribution of the H10 sample by plotting with heavy black points in the sample of Lusso et al. (2010) which contains 88% of the 408 AGNs in H10. Overall, our sample is brighter than H10’s in \( L_{\text{bol}} \) and less extensive in \( L_{\text{bol}} \) but more extensive in redshift space coverage than M11. From Figure 10, we find that the \( L_{\text{bol}} \) and \( r \)-band limits (Section 2) introduce a faint-end luminosity cut that is variable with redshift. Moreover, the anticorrelation between \( L_{\text{bol}} \) and the hot dust covering factor \( C_{\text{Fhd}} \) (see, e.g., M11) may act as a luminosity selection effect (Section 5.1) to mix up the distributions of \( f_{2.3} \) or \( C_{\text{Fhd}} \) when plotted against a parameter closely associated with \( L_{\text{bol}} \), such as \( M_{\text{BH}} \) or \( f_{\text{Edd}} \). To minimize any such effect, we split the whole sample into four volume-limited subsamples where 204 dust-poor quasars remain inside the dot–dashed limits in Figure 10(a).

Now we use the fraction of dust-poor quasars (\( p_{\text{dpp}} \)) to visualize the global trends of dust-poor quasars in observed parameters. When the \( p_{\text{dpp}} \) are plotted against \( L_{\text{bol}} \) (Figure 11(a)), we find a positive correlation between the two products, in accord with the distribution of \( f_{2.3} \) decreasing with \( L_{\text{bol}} \) in Figure 11(c). The first parameter to look into through \( p_{\text{dpp}} \) under the volume limits is the redshift, as we would like to know the evolution of the fraction of dust-poor quasars independent of luminosity selection. In Figure 11, we find not only a trend of lower \( f_{2.3} \) at higher redshift overall (Figure 11(d)), but also a clear
Figure 10. (a) Redshift–bolometric-luminosity and (b) black-hole-mass–Eddington-ratio distributions of our sample. The range of data points from M11 is highlighted for comparison (dashed lines). Furthermore, the 361 XMM-COSMOS spectroscopically confirmed type 1 AGNs from Lusso et al. (2010) that are similar to the sample of H10 are overplotted (black circles). Since the full sample is large, a quarter of the sample was randomly selected and plotted (black dots) in each panel, to better resolve and compare the overall distribution with that of dust-poor objects (colored circles). We subdivide our sample into four bolometric luminosity bins (dot–dashed lines) so that the analysis will be independent of luminosity selection effects.

Figure 11. Left: (a) plot of hot dust-poor fraction ($p_{\text{dhp}}$) vs. $L_{\text{bol}}$. Colored filled symbols represent the fraction of quasars in each luminosity bin that are hot dust-poor. The error bars are calculated based on Poisson statistics. (c) Plot of $f_{2,3}$ vs. $L_{\text{bol}}$. The individual distribution of hot dust-poor quasars (purple) is plotted with a randomly selected quarter (following Figure 10) of the entire sample (black). In addition, the average $f_{2,3}$ along $L_{\text{bol}}$ is overplotted (solid line). Right: (b) plot of $p_{\text{dhp}}$ vs. $z$. Colored filled symbols (slightly shifted to avoid overlap) represent the fraction of quasars in each luminosity and redshift bin that are hot dust-poor, with the number of objects per data point shown following the arrangement of the data. The open circle is the $z=6$ result of J10. Upper limits in $p_{\text{dhp}}$ are calculated as $1/N_{\text{dhp}}$ when there are no dust-poor quasars in the bin with size $N_{\text{dhp}}$. The gray circles are test results for our $z<1$, $K$- and W4-detected sample SEDs, simulated for each redshift and observed $i$-band magnitude. (d) Plot of $f_{2,3}$ vs. $z$. The layout follows panel (c).

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

tendency of increased $p_{\text{dhp}}$ at higher redshifts at given luminosity (Figure 11(b)), mixed with the $p_{\text{dhp}}$ increasing with luminosity at a given redshift. Compiling our $p_{\text{dhp}}$ with that inferred from J10, we fit the $z>2$, $L_{\text{bol}}>10^{47}$ erg s$^{-1}$ data points in Figure 11(b) to model the redshift evolution of the dust-poor fraction as $p_{\text{dhp}}=(1.35\pm 0.13)\times 10^{-3}(1+z)^{2.34\pm 0.08}$.

Since we are dealing with a small number of special objects, some of the dust-poor quasars could be misclassified normal
quasars due to large photometric errors or sparse wavelength sampling in the WISE data points. To estimate what fraction of dust-poor quasars could have arisen from these artifacts, we selected 7834 SDSS DR7 quasars in our sample at $z < 1$ with $K$ and $W4$ detections and redshifted their SEDs while adding appropriate noise to make them appear to have $z > 1$, starting from a set of observed fluxes and errors with $K$ adding appropriate noise to make them appear to have $z > 1$.

![Figure 12](image)

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

The figure indicates that the objects selected for this test are representative of general quasars at $z < 1$, since the simulated $p_{hdp}$ values, regardless of test magnitude, are within the errors of the observed $p_{hdp}$ at $z < 1$. But then, the test gives the possibility of dust-rich ($f_{2.3} > -0.5$) quasars being artificially classified as dust-poor, as the simulated $p_{hdp}$ starts to increase at $z > 1$. Not only does $p_{hdp}$ increase for fainter simulated magnitudes, it also has a peak at $2 < z < 3$ where the rest-frame $2.3 \mu m$ lies between the widely separated W2/W3 bands. This indicates that the dust-poor selection becomes uncertain when the photometric data points around the peak of the hot dust radiation are sparse. Comparing the observed versus simulated $p_{hdp}$ of $L_{bol} = 10^{46.5} - 10^{47}$ erg s$^{-1}$ sources in Figure 11(b), for example (yellow and gray points), we estimate that ~60% of the faintest objects ($i = 18.5-19$; see Figure 2(b)) in the dust-poor sample might be misclassified normal or borderline quasars at $2 < z < 3$. However, at $z > 3$ only a small fraction of dust-poor quasars are possible misclassifications, suggesting that the observed $p_{hdp}$ are genuinely higher at $z > 3$. Furthermore, taking into account the higher possibility of identifying false dust-poor objects at $2 < z < 3$, the intrinsic distribution of true dust-poor quasars will show a stronger positive $p_{hdp}$ trend at $z > 2$ for any given luminosity bin. Therefore, we consider the overall trend of increased $p_{hdp}$ with redshift to remain unchanged under the possible artifacts.

Next, $p_{hdp}$ versus black hole mass and Eddington ratio are plotted in Figures 12(a) and (b) for four different $L_{bol}$ bins. We find higher $p_{hdp}$ for more luminous $L_{bol}$ binned subsamples, which is consistent with Figures 11(a) and (b) and with predictions of smaller dust covering factors at brighter $L_{bol}$, such as from the receding dust torus model (Lawrence 1991). Therefore, we note the importance of controlling the range of $L_{bol}$ in order to accurately trace the properties of dust-poor quasars. In addition, because our dust-poor quasars are systematically smaller in $C_{Fd}$ or, equivalently, larger in NIR bolometric corrections ($BC = BC_{bol}$) than average, we would like to double-check whether the $L_{bol}$–$p_{hdp}$ trend is affected by systematically different BCs for dust-poor SEDs. We integrated the model fit on the composite photometric SED of all quasars (Figure 4) in the 0.04–20 $\mu m$ range, to find $L_{0.04-20}/L_{bol} = 6.46$, or 70% of the bolometric luminosity to be bounded within the selected UV–MIR wavelengths, adopting $BC_{bol} = 9.26$
from S11. Now, assuming that the SEDs of the average and dust-poor composites do not systematically vary with each other in the γ-ray/X-ray or FIR/radio (see Section 5.1 and Table 3 for the assumption to roughly hold for X-ray and radio wavelengths), \((L_{<0.04} + L_{>20})/L_{0.51}\) was \(2.80 = (L_{<0.04} + L_{>20})/L_{0.51}\). From our measurement of \((L_{<0.04} - L_{>20})/L_{0.51}\) was 5.04 out of the composite dust-poor SED, we obtain \(BC_{0.51} = 7.84\), meaning that bolometric luminosities of dust-poor quasars are about 18% overestimated with respect to ordinary quasars, under the adoption of a single \(BC_{0.51} = 9.26\).

Drawing Figures 11 and 12 again with an 18% smaller \(BC_{0.51}\) for dust-poor quasars, however, does not change the strength of the \(p_{\text{hdp}}\) trends found in \((z, L_{\text{bol}}, M_{\text{BH}}, f_{\text{edd}})\)-spaces. Therefore, we conclude that possible systematic biases in the bolometric correction for dust-poor quasars does not artificially produce the \(L_{\text{bol}}-p_{\text{hdp}}\) relation or change the observed \(p_{\text{hdp}}\) trends within the main observed parameters, although our test suggests caution when applying the BC to dust-poor quasars from the monochromatic luminosity alone. After all this, reading Figures 12(a) and (b) within each luminosity bin decoupled from the \(L_{\text{bol}}\) dependence on \(p_{\text{hdp}}\), we find more dust-poor quasars with lower black hole masses and high Eddington ratios.

Finally, we plot \(p_{\text{hdp}}\) against other AGN observables in Figure 13, starting from the broad-line width and velocity offset. We used the FWHMs from S11 as broad-line widths, updated and replaced for some dust-poor quasars as in Section 3. Meanwhile, we took the broad-line velocity offset measurements from S11, defined as the relative shift of the broad-line center with respect to the systemic redshift. The choice of broad line for the line width and offset measurements at each redshift was identical to that when measuring \(M_{\text{BH}}\) (Section 3), except that CIV line velocity shifts were not used, because of their overall blueshift (S11). There is a negative correlation between \(p_{\text{hdp}}\) and broad-line FWHM in Figure 13(a), consistent with the trend found for \(M_{\text{BH}}\), and a meaningful tendency for velocity offset toward blueshifted broad emission in Figure 13(b). The implications of these results are discussed in the next section. Next, reading Figure 13(c), dust-poor quasars with respect to the Fe II \((2200–3090 \, \text{Å})/Mg II \(\lambda 2798\) metallicity derived from S11 tend to have more iron-rich broad-line regions. Last, in Figure 13(d) we investigate the dependence of radio loudness on \(p_{\text{hdp}}\), with \(R_{\text{radio}} = F_{\nu, 6\, \text{cm}}/F_{\nu, 2500}\) from S11. The radio data are from the FIRST survey (Faint Images of the Radio Sky at Twenty cm; White et al. 1997), roughly coinciding with the SDSS coverage and reaching a typical 5σ sensitivity of 1 mJy. This is similar to the WISE \(W3\) sensitivity when assuming a flat source SED in \(F_{\nu}\) from MIR to radio, implying that most radio-loud/intermediate sources are radio detectable. However, the FIRST detection threshold (5σ) is higher than that of WISE (2σ) and misses the majority of radio-quiet sources, which results in only 10% of the final AGN sample used in this work being detected. Still, the radio loudness is roughly complete down to \(R_{\text{radio}} \sim 10\) within the detection limit, while the distribution of \(R_{\text{radio}}\) shows a trend expected to fail below \(R_{\text{radio}} \sim 10\) under nondetections, for both dust-poor and all AGNs. To further investigate the completeness of the radio data, we calculated the \(p_{\text{hdp}}\) in Figure 13(d) while adding the FIRST nondetections into the \(R_{\text{radio}} \sim 10\) bin, finding the \(p_{\text{hdp}}\) to be consistent within the errors, to that with the detections only. Ultimately, we find no significant preference of dust-poor quasars in the \(R_{\text{radio}}-p_{\text{hdp}}\) distribution. Likewise, we tried to search for the X-ray loudness features from the ROSAT All-Sky Survey observed counts in Schneider et al. (2010) but failed to compile enough matches \((N = 7)\) for proper analysis.

5. DISCUSSION

5.1. Observational Characteristics of Dust-poor Quasars

To quantify how distinct dust-poor quasars are from typical quasars in various physical properties, we performed a set of Kolmogorov–Smirnov (K-S) tests by comparing the distribution of the dust-poor sample against the average sample. The result is summarized in Table 3. Although it becomes uncertain at \(L_{\text{bol}} < 10^{46.5}\) erg s\(^{-1}\), most of the K-S probabilities at \(L_{\text{bol}} > 10^{46.5}\) erg s\(^{-1}\) are smaller than 1%, indicating that dust-poor quasars are likely to be drawn from a different population than average luminous quasars. Moreover, the directions of the inequality between dust-poor and average quasar properties in Table 3 are consistent with Figures 11–13. To begin summarizing the main results from the table and figures, dust-poor quasars are at higher redshifts for a given luminosity, with this trend found to be secure at \(z > 2\). This is consistent with J10 and H10, but not with M11, who did not find any evolution in the dust-poor fraction. Next, we find dust-poor quasars of relatively lower black hole mass, of order \(10^8\) \(M_{\odot}\), and high Eddington ratios indicating super-Eddington accretion, at a given luminosity, in agreement with J10 at \(z > 6\) but not with H10 or M11, where dust-poor quasars are indistinguishable from the

| Table 3 |
| K-S Test on Dust-poor Quasar Fraction in Observed Parameters |
|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Parameter      | \(p_{\text{KS}}\) | \(p_{\text{KS}}\) | \(p_{\text{KS}}\) | \(p_{\text{KS}}\) | \(N_{\text{hdp}}\) | \(N_{\text{hdp}}\) | \(N_{\text{hdp}}\) | \(N_{\text{hdp}}\) |
| \(z\)          | -0.09           | 3.1e-06         | 1.2e-03         | 0.13           | 18             | 60             | 93             | 33             |
| \(M_{\text{BH}}\) | -0.64           | -1.1e-04        | -7.7e-12        | -3.4e-03       | 18             | 60             | 90             | 25             |
| \(f_{\text{edd}}\) | 0.44            | 1.8e-07         | 1.6e-10         | 1.2e-04        | 18             | 60             | 90             | 25             |
| \(\text{FWHM}\) | -0.26           | -3.8e-04        | -7.3e-08        | -8.9e-03       | 18             | 60             | 90             | 25             |
| \(v_{\text{blueshift}}\) | 2.8e-03         | 2.9e-05         | 9.0e-11         | ...            | 18             | 60             | 40             | 3              |
| \(\text{Fe II/Mg II}\) | -0.26           | 3.8e-04         | 7.3e-08         | ...            | 16             | 60             | 50             | 3              |
| \(R_{\text{radio}}\) | 0.76            | 0.64            | 0.16            | -0.05          | 4              | 11             | 20             | 7              |

Notes. Here \(p_{\text{KS}}\) is the K-S probability of the distribution of dust-poor quasars in each parameter and luminosity bin being indistinguishable from that of the rest of our whole sample. The configuration of volume-limited luminosity bins follows Figure 10(a). Positive \(p_{\text{KS}}\) implies that dust-poor quasars have a larger parameter value than average quasars, and vice versa for negative values, while statistically meaningful probabilities, taken to be \(|p_{\text{KS}}| < 1\%), are printed in exponential format. \(N_{\text{hdp}}\) is the number of dust-poor quasars used in each bin to calculate \(p_{\text{KS}}\), ordered by the same luminosity range as for \(p_{\text{KS}}\). Blank fields correspond to bins without enough quasars to perform a test.

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average in $M_{\text{BH}}$ and $f_{\text{Edd}}$. In addition to these fundamental properties, dust-poor quasars show narrower broad-line FWHMs of 2000–3000 km s$^{-1}$, blueshifted line centers of order 10$^3$ km s$^{-1}$, and Fe$^{\text{II}}$/Mg$^{\text{II}}$ line ratios a few times higher than average.

Although we find some of the parameter trends summarized above to agree with previous studies, there are also debatable results. To investigate further among conflicting arguments, we first note the limitation of small number statistics. The number of our volume-limited dust-poor quasars is $N = 204$, which is enough to precisely look for parameter trends, as we find many of the K-S probabilities in Figure 3 to be statistically significant. Also, our study serves as a lower redshift counterpart to J10, as they miss the $z < 6$ dust-poor population, possibly because of a combination of the small parent sample size in J10 and the $z$–$p_{\text{hdp}}$ trend found in this work, which predicts fewer dust-poor quasars at lower $z$. Meanwhile, although H10 selected dust-poor quasars with a relatively high fraction ($\gtrsim 10\%$), their total of $N = 41$ dust-poor quasars is still insufficient to tell whether they are drawn from a different population or not, as the K-S probabilities lie ambiguously between 0 and 1 except with respect to the redshift. Therefore, a larger sample size would be required to understand in detail the dust-poor quasars defined in H10.

We additionally note that the X-ray selection of H10 brought discrepancies to the dust-poor population properties based on our optically selected AGNs. However, our $f_{\text{edd}} < -0.5$ limit is similarly met only for the class II criterion of H10, which is merely 15% of the dust-poor population in H10. Thus, we mostly regard the high $p_{\text{hdp}}$ in H10 as coming from the different definitions of being dust-poor rather than from the X-ray selection of AGNs to elevate the $p_{\text{hdp}}$.

Next, we note the difference of studying CF$_{\text{hd}}$ in overall distributions from previous works and under volume-limited subsampling here. For instance, the overall distribution of CF$_{\text{hd}}$ is roughly independent of $M_{\text{BH}}$ in J10 ($z < 6$), in M11, and in Figure 12(c). However, in Figure 12(a) we witness clearly higher $p_{\text{hdp}}$ for smaller $M_{\text{BH}}$ at a given luminosity of $L_{\text{bol}} > 10^{46.5}$ erg s$^{-1}$. If the sample had a wide dynamic range of $L_{\text{bol}}$, there would be a higher chance of the anticorrelation between $L_{\text{bol}}$ and CF$_{\text{hd}}$ mixing the distribution of CF$_{\text{hd}}$ when plotted against a parameter dependent on $L_{\text{bol}}$. In other words, quasars with higher $M_{\text{BH}}$ are more likely to be selected as dust-poor objects, since $M_{\text{BH}} \propto \sqrt{L_{\text{bol}}}$ (e.g., Equation (3) with constant BC) and because there are more dust-poor quasars with high $L_{\text{bol}}$ (Figure 11(a)). Revisiting Figure 12, this luminosity selection effect is indeed visible, where Figure 12(c), under a wide range of $L_{\text{bol}}$ displays flatter $f_{\text{dd}}$ with $M_{\text{BH}}$, or more chance of dust-poor quasars at higher $M_{\text{BH}}$, than Figure 12(a) under a fixed range of $L_{\text{bol}}$. Therefore, we expect the disconnection between $f_{\text{dd}}$ or CF$_{\text{hd}}$ versus $M_{\text{BH}}$ in the $z < 6$ population of J10 or M11 to be at least partially caused by a relatively broad range of $L_{\text{bol}}$ that would smooth out the possible underlying correlation between $M_{\text{BH}}$ and $f_{\text{dd}}$/$\text{CF}_{\text{hd}}$.

Likewise, the luminosity selection would act on the Eddington ratio as $f_{\text{edd}} \propto L_{\text{bol}}/M_{\text{BH}} \propto \sqrt{L_{\text{bol}}}$, selecting more dust-poor quasars at higher $f_{\text{edd}}$ than when volume limited. This time,
the positive $f_{\text{Edd}}-p_{\text{hdp}}$ relation of Figure 12(b) is consistent with the $f_{\text{Edd}}$–CF$_{\text{hd}}$ anticorrelation in Figure 12(d), which can be explained by the stronger $f_{\text{Edd}}$–CF$_{\text{hd}}$ anticorrelation than that of $L_{\text{bol}}$–CF$_{\text{hd}}$ (compare Figure 12(d) with Figure 11(c)). Furthermore, we expect the luminosity selection effect to be somewhat mixed by the redshift selection effect, as a result of the $z$–$p_{\text{hdp}}$ trend and the luminosity distribution of our sample, such that higher luminosity sources are at higher redshift on average. We tested the redshift selection effect by drawing figures similar to Figures 12(a) and (b) in a fixed $L_{\text{bol}} = 10^{47}$–$10^{47.5}$ erg s$^{-1}$ interval while comparing the $p_{\text{hdp}}$ between 1 < $z$ < 2 and 2 < $z$ < 3. We find a higher normalization of $p_{\text{hdp}}$ at higher redshift, but the difference in the $p_{\text{hdp}}$ is smaller than when the redshift interval is fixed as one of the two above, and instead subsamples in the range of $L_{\text{bol}}$ adjacent to the $10^{47}$ to $10^{47.5}$ erg s$^{-1}$ bin are compared. Therefore, the luminosity selection effect on $p_{\text{hdp}}$ in this work is only mildly mixed with that from redshift selection.

As a way to remove this effect, M11 defined their hot dust-poor quasars as the lower outlying objects in CF$_{\text{hd}}$, dependent on $L_{\text{bol}}$. Therefore, the $p_{\text{hdp}}$-based parameter trends of dust-poor quasars in M11 can be compared directly with the volume-limited $p_{\text{hdp}}$-based trends in this work, as both studies are corrected for luminosity selection, while the sample size of M11 is as large as ours, so they do not suffer from small number statistics. The $L_{\text{bol}}$–$p_{\text{hdp}}$ trend would be different for the two studies, though, as the definition of dust poorness in M11 inherently leads to a flat $p_{\text{hdp}}$–$L_{\text{bol}}$ relation, while our result of increasing $p_{\text{hdp}}$ with $L_{\text{bol}}$ is free from such a selection. Apart from this exception, we expect the $p_{\text{hdp}}$-related parameter trends from M11 and this work to be consistent with each other, but we still witness somewhat conflicting results in $z$, $M_{\text{BH}}$, and $f_{\text{Edd}}$-spaces. However, the redshift range of 0.75 < $z$ < 2 covered by M11 is not as wide as that of this work, which, according to Figure 11(b), implies they could miss up to an additional order of magnitude of the increase in $p_{\text{hdp}}$ above $z = 2$. Next, M11 did not find $p_{\text{hdp}}$ to depend on $M_{\text{BH}}$ or $f_{\text{Edd}}$, while we find negative and positive dependences on $M_{\text{BH}}$ and $f_{\text{Edd}}$, respectively. A caveat is that the dust-poor selection of M11 passes through ≥16% of the sample, which is much higher than the 0.6% from this work, or ∼1% from Figure 11(b) within the redshift interval 0.75 < $z$ < 2 matched with M11. From this, we suggest that M11’s method of selecting low-CF$_{\text{hd}}$ sources may choose too many objects as dust-poor, making it hard to distinguish properties of dust-poor quasars from the rest of the sample. To summarize, we conclude that the differences in $p_{\text{hdp}}$ trends between M11 and this work originate from the different redshift coverage and the selection criteria for dust-poor quasars.

We note that the observational characteristics of dust-poor quasars could be different at lower AGN luminosities, as our K-S probabilities in Table 3 are weaker at $L_{\text{bol}} < 10^{46.5}$ erg s$^{-1}$. Combining our results with the study of Mor & Netzer (2012, hereafter M12) helps to constrain the properties of fainter dust-poor AGNs, since their sample are Seyfert 1 galaxies mostly hereafter M12) helps to constrain the properties of fainter dust-poor AGNs, since their sample are Seyfert 1 galaxies mostly covering $L_{\text{bol}} = 10^{44}$–$10^{46}$ erg s$^{-1}$. Although their dust-poor and total sample sizes are only ∼10 and 115, they do find low-CF$_{\text{hd}}$ sources for narrow-line Seyfert 1’s in low $M_{\text{BH}}$ and high $f_{\text{Edd}}$, consistent with our results above $10^{46.5}$ erg s$^{-1}$. Since the optical luminosities of AGNs in M12 are likely to be affected by host galaxy contamination (see, e.g., S11), it would be interesting for future studies to check whether the parameter trends of intermediate-luminosity ($L_{\text{bol}} \lesssim 10^{46}$ erg s$^{-1}$) dust-poor AGNs, as in M12, are valid after correcting for host contamination in the optical luminosity.

Physically connecting our observational results of luminous dust-poor quasars, the $L_{\text{bol}}$–$p_{\text{hdp}}$ relation is well explained by the receding-torus model (Lawrence 1991), such that more luminous quasars have smaller dust covering factors as a result of the torus’s being located far from the central light source. In addition, the link between FWHM and $p_{\text{hdp}}$ in Figure 13(a) is closely connected with the $M_{\text{BH}}$–$p_{\text{hdp}}$ and $f_{\text{Edd}}$–$p_{\text{hdp}}$ relations in Figures 12(a) and (b), since quasars with narrow FWHM would be lower in $M_{\text{BH}}$ and higher in $f_{\text{Edd}}$ at a given $L_{\text{bol}}$. This implies that quasars that are not only luminous but also violent in growth and small in cumulative mass, or actively growing quasars, would have a higher chance of being dust-poor. Since our dust-poor quasars, although skewed to higher $z$, are fairly spread within the $z$–$p_{\text{hdp}}$ relation, we describe the dust-poor epoch of quasars as being positioned in a buildup state within individual black hole growth histories, rather than a specific global cosmic epoch (J10).

In addition to the key trends, the $v_{\text{off}}$–$p_{\text{hdp}}$ relationship for dust-poor quasars preferring blueshifted broad emission could be related to radiative outflows affecting the broad-line emission (e.g., Richards et al. 2011), which are necessary for radiative quasar feedback or QSO dust production through the expansion of broad-line clouds (Section 5.2). Alternatively, the blueshifts could be explained as recoiling black holes separated from the dusty torus (Guedes et al. 2011), but the predicted probabilities of detecting kinematically offset AGNs are still lower by several orders of magnitude than the fraction of our dust-poor quasars with large blueshifts. Meanwhile, the high FeII/MgII of dust-poor quasars could be a sign of metal seeds where QSO dust can grow (Section 5.2; Pipino et al. 2011), although it is difficult to arrive at a clear interpretation from observed metallicities alone.

5.2. The Origin of Dust-poor Quasars

We now consider possible scenarios for the origin of dust-poor quasars. First, we would like to list the explanations for the occurrence of dust-poor objects being dependent on the geometry of the surrounding dusty structure. One of the descriptions is the receding-torus model (Lawrence 1991), which predicts smaller dust covering factors at higher luminosities, for the obscuring structure to be located more outward. Our study provides further constraints for this model, as our dust-poor quasars are not only more luminous but also less massive and high in Eddington ratio. To fit our observational results, the viewing angle of dust-poor quasars could be considered as being observed from a face-on direction, because the unified model predicts obscuration from the dusty torus when observed through an inclined angle. Assuming that the broad-line region follows the inclination of the torus (Gaskell et al. 2007), and adopting a simplified planar geometry for these AGN substructures, the observed line widths would satisfy $FWHM_{\text{bol}} = FWHM_{\text{in}}$, where $i$ is the inclination angle. Therefore, we may expect the broad FWHMs of dust-poor quasars to be systematically narrower merely because of the projected sin $i$ factor for a planar geometry.

While this orientation-based approach is capable of explaining many parameter space features ($FWHM$, $M_{\text{BH}}$, $f_{\text{Edd}}$) of dust-poor quasars, the problem is that it cannot describe the redshift dependence of $p_{\text{hdp}}$ unless higher redshift quasars are systematically biased to lower inclination angle objects at given luminosity. Moreover, when a dusty torus is observed face-on, the unified model suggests more chance of being directly illuminated by radio jets (see, e.g., Figure 3 of Antonucci 1993).
whereas in Table 3 we do not find dust-poor quasars to be radio-louder, although the number statistics may not be secure. Several other geometric explanations of the origin of dust-poor quasars include low-level misalignment of the torus with respect to the accretion disk (Kawaguchi & Mori 2011) and mildly misaligned disks even without the torus structure (Lawrence & Elvis 2010). At this time, where our observations are not able to strictly validate each geometric scenario, we leave it as an open question to explain dust-poor quasars in a geometric sense, although we do stress the need for future models to be able to further explain our observational features (Section 5.1).

Second, in terms of the physical origin of dust-poor AGNs, that is, for intrinsic lack of dust emission under the dust blowout process, we would like to suggest in which stage dust-poor quasars would lie if they followed existing AGN evolutionary scenarios. With regard to the triggering of quasar activity, we follow Treister et al. (2012) and apply their result that within the luminosity limit of our study ($L_{\text{bol}} > 10^{45.7}$ erg s$^{-1}$), more than 50% of quasars are triggered by major mergers. Merger-triggered quasar activity is often observationally interpreted to begin from the stage of luminous infrared galaxies, showing strong signatures of dense gas and dust out to kiloparsec scales (e.g., Sanders et al. 1988; Surace et al. 1998). Therefore, for the majority of luminous dust-poor quasars to originate from galaxy merging, not only are the host galaxies expected to have been dusty during the merging stage, but the obscured host galaxies also require feedback mechanisms that blow out the surrounding material to become more transparent to the quasar radiation like normal quasar systems. This step is predicted in the merger-driven AGN model of Hopkins et al. (2008) as the blowout stage, where the gas and dust surrounding the quasar host galaxy are expelled.

Depending on the extent of merger-driven quasar feedback, red quasars are thought to be in the blowout stage when the surrounding dust has not yet been removed (e.g., Figure 5(e) in Hopkins et al. 2008; Urrutia et al. 2008), while we may now place dust-poor quasars at the end of the blowout stage for the dust to have sufficiently been dispersed. Our study further helps to observationally constrain the evolutionary boundary of dust-poor quasars, as we find it to agree with the blowout-phase predictions of rapidly growing black holes (low $M_{\text{BH}}$, high $f_{\text{edd}}$) and intense feedback (high $L_{\text{bol}}$ and blue UV continuum) from Hopkins et al. (2008), and with observations of high-$f_{\text{edd}}$ objects within the red quasar sample of Urrutia et al. (2012). At the same time, however, dust-poor quasars are closer to normal quasar phases, as their accretion-disk-dominated SEDs indicate that the nucleus is less obscured from its surroundings, compared with red quasars. Therefore, we consider it most plausible to assign dust-poor quasars between the blowout and traditional quasar phases, where dust-poor quasars can be explained as having just become unobscured as they went through intense feedback during the rapid black hole growth but are still relatively low in $M_{\text{BH}}$ and high in $f_{\text{edd}}$ on their way to becoming normal quasars. When our dust-poor fraction of 0.6% is translated into the visible dust-poor timescale, it becomes ~0.1–1 Myr from the visible timescale of quasar activity (Martini 2004; Hopkins et al. 2005). Therefore, the short visible timescale may imply either that dust can form efficiently after the short/intense dust-dispersing part of the blowout phase or that it is difficult for typical quasars to clear off the surrounding dust to a sufficient extent.

This approach to clarify the evolutionary state of dust-poor quasars from the key parameter trends would be strengthened if the redshift evolution of $p_{\text{hdp}}$ from this work were further explained. At high redshift, the amount of dust observed in quasars or gamma-ray bursts can be explained by dust-producing sources, mainly supernovae and the most massive asymptotic giant branch (AGB) stars, whereas QSO dust$^4$ or contributions from less massive AGB stars are relatively limited (see, e.g., Pipino et al. 2011; Jang et al. 2011). The restricted dust production routes within the short age of high-redshift quasar systems, therefore, could be the cause of the $z$–$p_{\text{hdp}}$ relation of dust-poor quasars, as their progenitors may not have enriched enough dust to survive under the presence of AGN feedback, observed to be in action up to the early universe (e.g., Maiolino et al. 2012). Hence, the increased fraction of dust-poor quasars at higher redshift is consistent with current dust formation model predictions and with observations of bluer UV continuum slopes of inactive galaxies at high redshift (e.g., Bouwens et al. 2009).

Stemming from the evolutionary model for dust-poor quasars, the fact that we find BAL quasars in our dust-poor sample has interesting implications for the dust origin of BAL quasars. Utilizing the BAL flag in S11 based on the criterion from Gibson et al. (2009), we find a BAL fraction of $4.3\% \pm 1.5\%$ from the dust-poor sample, similar to or only slightly higher than the $3.2\% \pm 0.1\%$ from the entire sample. As stated earlier, dust-poor quasars have a strong blue UV–optical continuum. If the BAL is caused by an orientation toward absorption (e.g., Elvis 2000), BAL quasars would not be included in the dust-poor sample, since the dusty structure would obscure the UV–optical light too. The evolutionary model for dust-poor quasars seems to provide a natural explanation for the dust in BAL quasars, supporting an evolutionary model of the BAL phase that lies between luminous infrared galaxies and normal quasars (e.g., Briggs et al. 1984; Lipari & Terlevich 2006).

5.3. The Future of Dust-poor Quasars

Having considered dust-poor quasars to possibly be explained by geometric or evolutionary models, to be observed by an unobscured orientation or to have undergone a duration of strong feedback, we would finally like to comment on their near future by comparing with average optically selected quasars. If dust-poor quasars have a geometric explanation, we may expect the covering factor to become larger at later quasar phases when they become quieter in luminosity or Eddington ratio, as the covering factors are anticorrelated with $L_{\text{bol}}$ and $f_{\text{edd}}$ (Lawrence 1991; Kawaguchi & Mori 2011).

On the other hand, assuming an evolutionary origin for dust-poor quasars, we need to consider dust formation mechanisms during the AGN evolution. Although our observational explanation of dust-poor quasars as rapidly growing (Section 5.1) supports their being younger than ordinary quasars, the evolutionary models predict the other way round, for quasars to become more dust-poor along the duration of their activity. This is due to the solely destructive nature of AGN feedback, to blow out the surrounding dust (e.g., Haas et al. 2003; Hopkins et al. 2008). Thus, assuming that the evolutionary paths for dust-poor and ordinary quasars are aligned—in other words, considering the dust-poor phase to be general within the lifetime of optically selected quasars—the only way to reconcile with observations is to add to the models constructive feedback from the AGN activity itself, which is to say, a dust formation mechanism at the center of quasars. This idea makes sense in that it satisfies the temporal causality to enrich the dusty tori as the system

$^4$ We use the term QSO dust for the dust production originating from the quasar activity and to distinguish from stellar-related sources.
accumulates its black hole mass. Our rapid-growth scenario therefore naturally supports the model production of QSO dust, possibly during the free expansion of broad-line clouds (Elvis et al. 2002), which is in fact likely to be the dominant source of dust formation in the inner galaxy once AGN feedback becomes effective (Pipino et al. 2011). To summarize, revising the evolutionary model for luminous quasars passing the dust-poor phase, dust blowout in the inner kiloparsecs of the galaxy is followed by dust formation from the central parsecs of the AGN.

Still, in the cases of powerful AGN feedback, one could imagine the intense radiation not only removing the galaxy-scale dust, but destroying the freshly formed QSO dust at the center of active galaxies such that dust-poor quasars remain dust-poor. This may not be the case for $L_{bol} < 2 \times 10^{47}$ erg s$^{-1}$ quasars, though, since the radiative flux density illuminating the QSO dust-forming region is weaker than that around giant stars (Elvis et al. 2002). Considering that 75% of our dust-poor quasars are less luminous than this limit, the extreme case of continued dust destruction can mostly be rejected as the fate of dust-poor quasars. Therefore, provided that the dust production is effectively working, we suggest the near future of dust-poor quasars to provide meaningful evolutionary predictions.

But what if dust-poor quasars are not causally related to ordinary quasars? It could be the case that dust-poor quasars are indeed rare objects within AGN evolution, to be placed in intrinsically dust-poor environments within their host galaxies and/or with weak QSO dust formation, such that they do not become as dust-rich as ordinary quasars during the quasar phase. This idea may be supported by observations of early-type AGN host galaxies, where the ratio of dust mass to $4.5 \mu m$ luminosity, representing the stellar mass (e.g., Jun & Im 2008), ranges widely at a given $4.5 \mu m$ luminosity (Martini et al. 2013). Within this framework, the relative lifetimes of each AGN evolutionary stage based on obscuration could be scattered as a result of the variety of dust content within each host environment. For example, although AGN evolutionary models predict obscured AGNs to be younger than the unobscured, under an especially low dust-to-stellar mass ratio environment of the host, AGNs would quickly become optically luminous without a typically long duration of being obscured (e.g., Hopkins et al. 2005). Thus, even if dust-poor quasars may be explained as lying in a rare dust-poor environment, this shifts the visible dust-poor lifetime to the relatively earlier growing stage of the black hole, still consistent with our rapid-growth explanation (Section 5.1).

6. CONCLUSION

Out of a large-area, multiwavelength sample of luminous quasars, we identified 233 (0.6%) objects that satisfy a hot dust-poor criterion analogous to that of Jiang et al. (2010). The selected dust-poor quasars are weak in both NIR- and MIR-to-optical flux ratios and show a blue continuum with mean slope of $\alpha \sim 0.1$ from the UV through the NIR. We calculated the fraction of dust-poor quasars in four bolometric luminosity bins and find statistical preferences of dust-poor quasars to be more abundant at higher redshift and to have lower black hole mass, higher Eddington ratio, blueshifted and narrower broad lines, and higher Fe II/Mg II ratio at a given luminosity. The results show that dust-poor quasars are a population that is rapidly growing in terms of $M_{BH}$ and $f_{edd}$, while the rapid growth of black holes and the dust poorness should be linked closely to the evolution of quasars as a function of redshift.

To explain the observational characteristics of dust-poor quasars, we suggest a scenario in which dust-poor quasars are transient phenomena during an evolutionary process, when they became unobscured by merger-driven AGN feedback. Luminous quasars are often triggered by violent major merging (Treister et al. 2012), involving large extinctions from their host galaxies (e.g., Sanders et al. 1988). From the onset of strong AGN activity, radiative feedback blows out (Hopkins et al. 2008) the surrounding galactic dust to produce dust-poor quasars, for a very short period if they produce QSO dust (Elvis et al. 2002; Pipino et al. 2011), or for longer if they are in an especially dust-poor environment. The redshift evolution of the dust-poor fraction is an indication of the dust content at different redshifts, where the dust-poor phase is more easily identified and lasts longer at higher redshift, since the elements that make up dust grains are scarce in the early universe. An alternative scenario would be to explain dust-poor quasars as a distinct population with small covering factors due to the geometry or orientation of the obscuring material. Such models (Lawrence 1991; Lawrence & Elvis 2010; Kawaguchi & Mori 2011) are consistent with most of the observed properties, but not with the redshift evolution of the dust-poor fraction.

We find the short timescale from the rare population of dust-poor quasars to provide meaningful evolutionary predictions. Deep and resolved imaging of the AGN hosts will tell us whether these dust-poor quasars are closely linked to the evolutionary phase, as the merging features would be clearer at earlier times than the rapid fading of tidal features (Hopkins et al. 2008). Besides, extrapolating the rough relation $P_{hdp} \propto (1 + z)^{-2.34}$ (Section 4.2) up to the early universe, we expect $P_{hdp} = 18\%$ and $P_{hdp} = 37\%$ or more for luminous quasars at $z = 7$ and $z = 10$, respectively. Therefore, discovery of the highest-redshift quasars will help us learn whether the higher incidence of dust-poor quasars, blue in UV continuum, boost the quasar contribution in reionizing the universe (e.g., Fan et al. 2006) or if they are born in extremely dust-poor galaxies, as hinted at by the UV slopes of low-luminosity galaxies at $z \sim 7$ (e.g., Bouwens et al. 2010). Future deep multiwavelength studies of dust-poor AGNs should place better constraints on the multitemperature dust emission of the AGN host system and the redshift evolution of these objects.

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ERRATUM: “PHYSICAL PROPERTIES OF LUMINOUS DUST-POOR QUASARS” (2013, ApJ, 779, 104)

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In the published version of this article, an error was found in Equation (3). The constant for the Hα black hole mass equation, \( a = 6.69 \), should be \( a = 6.99 \). This changes the black hole masses of the sample quasars at \( z < 0.37 \), but has a negligible effect on the results (Figures 10(b) and 12, Table 3) since in this redshift bin, only 0.6% of the sample are distributed with no dust-poor quasars in it. The K–S probabilities of the log \( L_{\text{bol}} = 45.7–46.5 \) column in Table 3 are shifted from −0.64 to −0.62 for \( M_{\text{BH}} \) and 0.44 to 0.43 for \( f_{\text{Edd}} \), which verifies the minimal change of the results due to the erratum.