HERSCHEL OBSERVED STRIPE 82 QUASARS AND THEIR HOST GALAXIES: CONNECTIONS BETWEEN AGN ACTIVITY AND HOST GALAXY STAR FORMATION

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ABSTRACT

In this work, we present a study of 207 quasars selected from the Sloan Digital Sky Survey quasar catalogs and the Herschel Stripe 82 survey. Quasars within this sample are high-luminosity quasars with a mean bolometric luminosity of $10^{46.4}$ erg s$^{-1}$. The redshift range of this sample is within $z < 4$, with a mean value of $1.5 \pm 0.78$. Because we only selected quasars that have been detected in all three Herschel-SPIRE bands, the quasar sample is complete yet highly biased. Based on the multi-wavelength photometric observation data, we conducted a spectral energy distribution (SED) fitting through UV to FIR. Parameters such as active galactic nucleus (AGN) luminosity, far-IR (FIR) luminosity, stellar mass, as well as many other AGN and galaxy properties are deduced from the SED fitting results. The mean star formation rate (SFR) of the sample is $419 M_\odot$ yr$^{-1}$ and the mean gas mass is $\sim 10^{11.3} M_\odot$. All of these results point to an IR luminous quasar system. Compared with star formation main sequence (MS) galaxies, at least 80 out of 207 quasars are hosted by starburst galaxies. This supports the statement that luminous AGNs are more likely to be associated with major mergers. The SFR increases with the redshift up to $z = 2$. It is correlated with the AGN bolometric luminosity, where $L_{\text{FIR}} \propto L_{\text{bol}}^{0.46 \pm 0.03}$. The AGN bolometric luminosity is also correlated with the host galaxy mass and gas mass. Yet the correlation between $L_{\text{FIR}}$ and $L_{\text{bol}}$ has higher significant level, implies that the link between AGN accretion and the SFR is more primal. The $M_{\text{BH}}/M_*$ ratio of our sample is $0.02$, higher than the value $0.005$ in the local universe. It might indicate an evolutionary trend of the $M_{\text{BH}}$–$M_*$ scaling relation.

Key words: galaxies: active – galaxies: evolution – galaxies: starburst – galaxies: star formation – quasars: general – techniques: photometric

Supporting material: machine-readable table

1. INTRODUCTION

The supermassive black hole (SMBH) is a common component residing in many galactic centers. SMBH mass is known to be correlated with its host galaxy properties, such as bulge mass and velocity dispersion (e.g., Kormendy & Richstone 1995; Magorrian et al. 1998; Ferrarese & Merritt 2000; Gebhardt et al. 2000; Tremaine et al. 2002). Furthermore, both cosmic star formation and black hole accretion activity peak around $z = 2$ and decrease toward lower redshifts (e.g., Boyle et al. 1998; Madau & Dickinson 2014). It seems that sub-pc-scaled BH accretion and kiloparsec-scale star formation are somehow entwined. Yet how SMBHs are fueled and how star formation is triggered, as well as the interactions between these two processes, are still under discussion.

It is well known that star formation rate (SFR) and stellar mass in star-forming galaxies follow a tight correlation. This so-called star-forming main sequence (MS) is thought to reflect a large duty cycle of star formation in galaxies and exist over a large range of redshifts from $z = 0$ up to $z = 7$ (Brinchmann et al. 2004; Daddi et al. 2007, 2009; Elbaz et al. 2007; Noeske et al. 2007; González et al. 2011). Starburst galaxies are considered to be “off-sequence.” Differing from MS galaxies, where star formation is caused by internal secular processes, star formation in starburst galaxies is triggered by gas-rich major mergers and has higher star formation efficiency (Daddi et al. 2010; Genzel et al. 2010). Mullaney et al. (2012) studied an X-ray-selected moderate-luminosity ($L_X < 10^{42}$–$10^{44}$ erg s$^{-1}$) active galactic nucleus (AGN) sample with $z < 3$, and found that 79 ± 10% of AGNs reside in massive, normal MS galaxies. It seems that AGN evolution is dominated by a non-merger process. Other studies about AGN hosts reach similar conclusions, such as Kocevski et al. (2012), Santini et al. (2012), and Schawinski et al. (2011). Their results provide evidence that the starburst galaxies only account for 10% of the cosmic SFR density at $z \sim 2$ (Rodighiero et al. 2011; Lamastra et al. 2013). Yet, Treister et al. (2012) found that the mergers are responsible for triggering the most luminous AGNs ($L_{\text{bol}} > 10^{45}$ erg s$^{-1}$). These studies imply that host galaxies of moderate luminous AGNs and the most luminous AGNs evolve along different paths. Thus, the relation between AGN luminosity and SFR is also dependent on AGN luminosity.

A correlation between SFR and AGN luminosity has been found for high-luminosity AGNs. For instance, Schweitzer et al. (2006) used PG quasars and found a correlation between AGN luminosity and polycyclic aromatic hydrocarbon (PAH) luminosity; Lutz et al. (2008) studied $12 \lesssim z \lesssim 2$ millimetre-bright type 1 quasars (with optical luminosity $L_{3100} = 10^{45}$–$10^{47}$ erg s$^{-1}$) and found a correlation between PAH luminosity and $L_{3100}$; Lutz et al. (2010) found an increasing of SFR with AGN luminosity at the highest X-ray ($L_{2-10\text{keV}} \geq 10^{44}$ erg s$^{-1}$) luminosities; Bonfield et al. (2011) used optically selected quasars ($10^{45} < L_{\text{bol}} < 10^{48}$ erg s$^{-1}$) and found a correlation between AGN luminosity and SFR. These luminous AGNs are likely to be fueled by rapid gas infall associated with major mergers of gas-rich galaxies (e.g., Hopkins et al. 2006, 2008; Somerville et al. 2008).

SMBHs in low- and moderate-luminosity AGNs are believed to be fueled by secular processes (e.g., Hopkins et al. 2006;
Jogee 2006; Younger et al. 2008). Many studies focused on these AGNs, yet no strong correlations between AGN luminosity and SFR (or IR luminosity) were found. For example, Shao et al. (2010) found little dependence of far-infrared luminosity on AGN luminosity for $L_{2-10\text{ keV}} \lesssim 10^{44}\text{ erg s}^{-1}$ AGNs at $z > 1$; Mullaney et al. (2012) found no relation between $L_{\text{FIR}}$ and $L_{\nu}$ with X-ray-selected moderate luminous quasars ($L_{\nu} \sim 10^{42-10^{44}}\text{ erg s}^{-1}$); and Rosario et al. (2012) found that $L_{60}$ is independent of $L_{\text{AGN}}$ at low accretion luminosities, but shows a strong correlation with $L_{\text{AGN}}$ at high accretion luminosities. These studies again indicate that AGN growth follows two different paths: low or moderate luminous AGNs evolve through secular processes and are not directly linked to the states of their host galaxies, while high-luminosity AGNs evolve through major mergers and might have a direct link between black hole growth and bulge growth.

In this paper, using a quasar sample selected from the Sloan Digital Sky Survey (SDSS) Stripe 82, we aim to study AGN activity and the star formation of its host galaxy. In galaxies, most of the radiation from the newly formed stars is absorbed and reemitted at infrared wavelengths. Therefore, IR luminosity can be used to estimate SFR. Yet AGNs can also heat the dust and bring contamination to IR luminosity. A popular method to most of the radiation from the newly formed stars is absorbed and bring contamination to IR luminosity. A popular method to

Digital Sky Survey (Abazajian et al. 2009); and the SDSS quasar catalog from the tenth data release (DR10Q hereafter; Pâris et al. 2014). The search radius is 5 arcsec. The HerS catalog is a band-merged catalog with 250 μm sources as positional priors and only includes sources with signal-to-noise ratio greater than three. In order to achieve a reliable SED fitting at the FIR, we only selected sources detected at all three SPIRE bands from HerS. The resulting sample is highly biased toward luminous FIR sources. Because of this flux limitation, our sample is affected by the Malmquist bias, of which we will give a more detailed discussion in later sections. There are 226 quasars in the entire sample, where 153 are from DR7Q and 73 from DR10Q. The redshift of the sample is smaller than 4, with a mean redshift of 1.54. The mean flux at 250 μm is 53.7 mJy, and the average i-band AB magnitude is 19.4 mag.

2. SAMPLE SELECTION AND DATA COLLECTION

SDSS Stripe 82 covers approximately 270 deg$^2$ area on the celestial equator in the south Galactic cap, spanning from 20° to 4° in R.A. and $-1°25 \sim 2°25$ in decl. (Adelman-McCarthy et al. 2007). It has been repeatedly imaged by SDSS between 1998 and 2007. Besides the optical imaging survey and the spectroscopic survey, SDSS Stripe 82 has also been observed extensively by other surveys from X-ray through UV/optical to IR and radio bandpasses. For example, the UKIRT Infrared Deep Sky Survey (UKIDSS; Lawrence et al. 2007) and the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006) at near-IR, the Wide-Field Infrared Survey (WISE; Wright et al. 2010) at mid-IR, and the Herschel Stripe 82 Survey (Hers; Viero et al. 2014) at far-IR. Among these surveys, Hers, an imaging survey conducted by SPIRE on board the Herschel Space Observatory, covers about 79 deg$^2$ in area to an average depth of 13.0, 12.9, and 14.8 mJy beam$^{-1}$ (including a confusion limit of 7 mJy) at 250, 350, and 500 μm, respectively. It is particularly suitable for studying the FIR excess of quasars, which are generally interpreted as contributions from star formation in their host galaxies.

The quasar sample is selected by cross-identifying the HerS catalog with the Shen et al. (2011) quasar catalog (DR7Q hereafter), the compiled catalog based on the spectroscopic quasar catalog (Schneider et al. 2010) from SDSS Data Release 7

2.1. Optical Photometric Measurements and Spectral Parameters

The SDSS imaging survey includes five optical bandpasses: $u$ (3543 Å), $g$ (4770 Å), $r$ (6231 Å), $i$ (7625 Å), and $z$ (9134 Å). The scale plate of SDSS is 30 arcsec$^2$. The mean $i$-band PSF magnitude is 19.4 mag. Some low redshift quasars in the sample show up as extended sources on the SDSS images. Therefore, we use “CMODEL magnitude” instead of “PSF magnitude.” We also remove quasar emission lines (i.e., $H_{\alpha}$, $H_{\beta}$, $Mg_{\pi}$, and $C_{\pi}$) by convolving the continuum-subtracted spectra with relevant filters from each bandpass. The SDSS magnitudes are converted to physical fluxes based on Fukugita et al. (1996). Shen et al. (2011) provides DR7Q with the FWHM of emission lines, such as $H_{\alpha}$, $H_{\beta}$, $Mg_{\pi}$, and $C_{\pi}$. Other useful parameters to our work are bolometric luminosity, monochromatic luminosities (at 1350 Å, 3000 Å, and 5100 Å, respectively) and virial BH mass. They are used as sanity checks for our results. The SDSS quasar catalog DR10 provides the FWHM of $Mg_{\pi}$ and $C_{\pi}$ emission lines.

2.2. FIR/sub-mm Photometry

FIR data are from the Herschel Stripe 82 Survey (Viero et al. 2014), which consists of 79 deg$^2$ of contiguous imaging with the SPIRE instrument (Griffin et al. 2010) on the Herschel Space Observatory (Pilbratt et al. 2010). The confusion limit is about 7 mJy at all three bands. The point-source catalog of the HerS in the three bands was produced as follows.

1. Map filtering to remove large-scale Galactic cirrus. Maps were constructed using the maximum likelihood mapper SANEPIC (Signal and Noise Estimation Procedure Including Correlations; Patanchon et al. 2008), which separates the low-frequency correlated noise from the sky signal, therefore, better preserves the large-scale variations of the sky.
2. Source identification to identify point sources in the filtered 250 μm image using the IDL software package STARFINDER (Dolaiti et al. 2000) with a Gaussian PSF. The FWHM of the PSF is 18.15, 25.15, and 36.3 arcsec for 250, 350, and 500 μm, respectively.
3. Source photometry to measure source photometry using a modified De-blended SPIRE Photometry algorithm (Roseboom et al. 2010, 2012).

The band-merged catalog is constructed using 250 μm sources as positional priors, and only included sources with...
2.3. Near-IR Data

2MASS is a near-IR imaging survey. It contains three filters: $J$ (1.25 μm), $H$ (1.65 μm), and $K_s$ (2.16 μm). At the 10-σ level, the photometric sensitivity of the point-source catalog is 15.8, 15.1, and 14.3 mag at $J$, $H$, and $K_s$ respectively. The best image of 2MASS has an FWHM of 2.5″. We match with 2MASS using a cross-radius of 5″ and find that 90 objects have detections in at least one bandpass. We choose the profile-fit photometry magnitude from the catalog, and convert the Vega-based magnitude to physical flux based on Cohen et al. (2003). UKIDSS is another near-IR imaging survey. It carries the following bandpasses: $Y$ (1.03 μm), $J$ (1.25 μm), $H$ (1.63 μm), and $K$ (2.20 μm). It is a $K$ band magnitude limited survey with a $K$-band depth of 18.4 mag. We match it with UKIDSS DR10PLUS via the WFCAM science archive using a cross-radius of 5″. Of 222 quasars, 135 result in four band detections, 18 quasars have at least two band detections, and 8 quasars only have one band detection. We adopt the aperture-corrected magnitudes YAPERMAG3, JAPERMAC3, HAPERMAC3, and KAPERMAC3. They are also converted to physical fluxes based on Hewett et al. (2006).

2.4. Mid-IF Data

WISE maps the sky using four filters centered at 3.4, 4.6, 12, and 22 μm, with an angular resolution of 6.1, 6.4, 6.5, and 12.0 arcsec, respectively. Of 222, 215 have matched counterparts in the AllWISE catalog with a match radius of 5″. We retrieve profile-fitting magnitudes from the catalog and convert them to physical fluxes based on Wright et al. (2010).

Before SED fitting, the Galactic reddening is corrected based on (Schlegel et al. 1998). The K-correction is also applied assuming a power-law SED with index $\alpha_\nu = -0.5$. Throughout this paper, we assume cosmological parameters $h = 0.7$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$.

3. SED FITTING

3.1. SED Fitting Components

In general an observed quasar SED can be decomposed to the following components: a power-law representing the UV/optical emission from the accretion disk; a torus representing IR emission from the dusty torus; a host galaxy when the contamination from stellar light is noticeable; and sometimes an FIR excess contributed by star formation. The wavelength range we used for SED fitting is from 0.15 to 500 μm at the rest frame. The custom-written SED fitting routine uses Python “Imfit,” a least-squares minimization package with bands and constraints. The Levenberg–Marquardt algorithm is used to minimize the $\chi^2$ and provide the standard errors.

3.1.1. Power-law Component

The accretion disk emission at the UV/optical regime can be described by a power-law function, $F_\nu \propto \nu^{\alpha}$. We extend this component to the NIR as suggested in Hönig & Kishimoto (2010) where $F_\nu \propto \nu^{\alpha}$, when $\nu \geq 3 \mu m$. The reason to start from 0.15 μm is to avoid the contamination from Lyα emission line (see Richards et al. 2006 for a discussion of how emission lines affect broadband photometry). The free parameters are the index $\alpha$ and the scale.

3.1.2. Torus

The Unification Scheme of AGNs requires a toroidal region filled with molecular gas and dust to explain the observed broad-line and narrow-line quasars. Dust in the torus is heated up by UV/optical emission from the accretion disk and radiates at infrared. This thermal emission from the torus dominates the near- to mid-IR emissions of quasars, and peaks around 10–20 μm. The torus models used in the SED fitting are from clumpy torus models (CAT3D) by Hönig & Kishimoto (2010). For each model, torus SEDs are calculated with inclination of 0° to 90° with an interval of 15°. Because SDSS quasars are mostly Type I AGNs, we only use models with inclination of 0° and 45°. The total number of torus models is 480. They can be scaled to match different quasars. Many SED analyses find an extra luminosity bump at 2-4 μm; it is emitted by hot dust at the innermost part of the standard clumpy torus (e.g., Barvainis 1987; Mor et al. 2009; Mor & Netzer 2012). This hot dust emission is modeled by a blackbody component with a temperature of 1300 K, the typical sublimation temperature of hot dust.

3.1.3. Host Galaxy Component and Internal Extinction

The observed quasar image is a combination of both an AGN and its host galaxy. Depending on the relative intensity of the host to the AGN, a host component could be needed to yield a good SED fit. De-blending a point-source-like quasar from an extended host is not easy especially at z > 1. Many quasars also suffer internal reddening (e.g., Webster et al. 1995; Young et al. 2008), which brings further complications into determining the quasar’s SED at the UV and optical bandpasses.

Hao et al. (2013) developed a “quasar-galaxy mixing diagram” to estimate the host galaxy contribution fraction, $f_{\text{fg}}$, at 1 μm by using its SED slopes from 1 μm to 3000 Å ($\alpha_{\text{opt}}$) and from 1 to 3 μm ($\alpha_{\text{NIR}}$) in the rest frame. The reason behind the “quasar-galaxy mixing diagram” is that the Wien tail of the blackbody thermal emission from the hottest dust starts to outshine the power-law emission from the accretion disk at the optical bandpass. As a result, the SEDs of a quasar and a galaxy at near 1 μm are completely different. Quasars, with their SEDs showing a clear dip at 1 μm, are located on the mixing diagram where $\alpha_{\text{opt}} > 0$ and $\alpha_{\text{NIR}} < 0$. Galaxies, with their SEDs peaking around 1–2 μm, are located on the mixing diagram...
where $\alpha_{\text{opt}} < 0$ and $\alpha_{\text{NIR}} > 0.8$, instead. Hao et al. (2013) also found that objects affected by quasar internal reddening move almost perpendicularly to the line that joins the AGN locus and galaxy locus on the mixing diagram. Based on an object’s location, the mixing diagram allows us to estimate the host galaxy contribution, $f_g$, as well as its internal reddening ($A_{\text{int}}$). This process is illustrated in Figure 1. Based on the quasar-galaxy mixing diagram, 93 quasars have $f_g > 0.1$. We select two galaxy templates from the SWIRE Template Library (Polletta et al. 2007): an Sb galaxy representing the younger stellar population and an elliptical galaxy (E) representing the older stellar population. Galaxy templates are scaled to match $f_g$ throughout the SED fitting. The reddening of the quasar is also given by the quasar-galaxy mixing diagram. In this sample, 134 quasars have noticeable reddening with an average reddening of $0.16 \pm 0.053$ mag. They are used to correct the internal reddening assuming an SMC reddening law as suggested in Hao et al. (2013).

### 3.2. SED Results

We apply the SED fitting on our sample. Some quasars are removed from further analysis and we give explanations below.

#### 3.2.1. Power-law Component

The mean power-law slope from our result is $0.031 \pm 0.33$, steeper than the UV/optical spectra index of $-0.44$ (Vanden Berk et al. 2001). The steeper spectra index is because we have corrected the internal reddening of the quasar. An SED fitting without the internal reddening correction yields a mean power-law slope of $-0.38 \pm 0.32$ instead.

#### 3.2.2. Host Galaxy Component

As described in the previous section, we estimate the host galaxy fraction, $f_g$, and the internal reddening using the “quasar-galaxy mixing diagram” from Hao et al. (2013). The mixing diagram assumes that the quasar SEDs are similar to the mean SED of Elvis et al. (1994) and the internal extinction of quasars follow the SMC reddening law. Scott & Stewart (2014) demonstrates that the Elvis et al. (1994) SED template agrees with other templates such as Richards et al. (2006) and Shang et al. (2011). It also appears to vary little with cosmic evolution or different Eddington ratio (Hao et al. 2011).

![Figure 1. Example for estimating the host galaxy contribution fraction and internal reddening using $\alpha_{\text{opt}}$ and $\alpha_{\text{NIR}}$. The quasar broadband photometric measurements are represented by black crosses with blue error bars. $\alpha_{\text{opt}}$ is the slope from 0.3 to 1 $\mu$m. $\alpha_{\text{NIR}}$ is the slope from 1 to 3 $\mu$m. The inset is the quasar-galaxy mixing diagram. The grids are generated for an Sb and an elliptical galaxy assuming an SMC reddening law. The far right corner of the grid, marked with a red asterism, represents the quasar mean SED with both $f_g$ and reddening equal to zero. The $f_g$ increases toward the upper left corner with an interval of 0.1. The reddening increases toward the lower left corner with an interval of 0.1 mag. The blue asterism indicates the location of the quasar on the quasar-galaxy mixing diagram, which yields an $f_g$ of 0.5 and reddening of 0.5 mag.](image-url)
demonstrates that there is little difference among generally used extinction curves, such as SMC, LMC, and MW. Here we choose the SMC extinction curve because it is more commonly used in quasars (Hopkins et al. 2004; Gallerani et al. 2010). The accuracies of α_{opt} and α_{NIR} depend highly on the availability and quality of photometric measurements. The average photometric measurement used for α_{opt} is 8, and for α_{NIR}. There are 22 objects with only one photometric measurement within 1–3 μm. Hao et al. (2013) warns against including longer wavelengths (>3 μm), because they will bring extra uncertainties to NIR. For those 22 objects, we fit the α_{opt} first, then use the extrapolated photometric value at 1 μm and the measurement from observation to calculate the slope α_{NIR}. As expected, these 22 objects have higher mean errors in both f_ν and the internal reddening, with f_νErr = ±0.12 and A_{ν}Err = ±0.06 mag, compared to the remaining objects with f_νErr = ±0.056 and A_{ν}Err = ±0.04 mag, respectively. Using f_ν and A_{ν} as priors, we find that 93 quasars required a component of the host galaxy (i.e., f_ν > 0.1). After the SED fitting, 44 quasars can be fitted with an Sb template, and the remaining 49 quasars are better suited with an elliptical template.

3.2.3. NIR and MIR Dust

As mentioned before, AGN emission has two luminosity bumps at NIR and MIR; one is around 10–20 μm from a clumpy torus, the other around 2–4 μm from hot dust at the innermost region of the standard torus. CAT3D models can describe the clumpy dusty torii, but cannot produce the 2–4 μm bump. Without an extra hot-dust component, SED fitting will favor the torus models with smaller open-angles, or increase the scale of the torus to match the NIR bump. Therefore, an AGN will have a greater contribution toward the FIR, resulting in colder FIR dust. Adding a hot-dust component helps constrain the torus model, and as a result, indirectly constrains the FIR dust component as well. Mor & Trakhtenbrot (2011) shows that a hot-dust component is present in more than 80% of type I AGNs. We find a slightly higher percentage (89%) as 202 out 227 quasars need a hot-dust component.

3.2.4. FIR Dust Temperature

For high-z quasars, the additional FIR component can be modeled as a graybody with a temperature of 40–60 K (Leipski et al. 2013). Yet the typical dust temperature at ultra-luminous infrared galaxies (ULIRGs) can be as low as 25–35 K (Hwang et al. 2010). Thus, the FIR dust temperature is allowed to vary from 10 to 60 K. The initial temperature is set to be 44 K, the mean FIR dust temperature of the high-z quasars (Beelen et al. 2006; Leipski et al. 2013). To achieve a reliable temperature, the FIR data should be sampled around the peak of the SED at FIR. Yet, with only three Herschel-SPIRE bandpasses, it is not always possible depending on the redshift. Using Monte-Carlo simulation to estimate the temperature errors, we find that the mean value of the temperature to the temperature error ratios of our SED fitting is 8.6, while only eight objects have ratios smaller than 3. Therefore, we believe that the temperature estimated through SED fitting is robust. Recently, Ma & Yan (2015) studied a sample from the optical-selected SDSS quasars and Herschel very wide-field surveys. They conducted their FIR SEDs using two methods: a single-temperature modified blackbody spectrum and a set of starburst templates. By comparing our sample with their work, we find 62 common quasars with both temperature to temperature error ratios larger than 3. The effective temperature of our results is about 10 K lower and the FIR luminosity is about 0.2 dex fainter compared to Ma & Yan (2015). It might be due to the fact that we exclude AGN contribution at the FIR. Beelen et al. (2006) detected six high-redshift (1.8 ≤ z ≤ 6.4) optically luminous radio-quiet quasars at 350 μm using the SHARC-II bolometer camera at the Caltech Submillimeter Observatory. They found the mean value of the graybody temperature was 47 ± 3 K with a dust emissivity index of β = 1.6 ± 0.1. The FIR luminosities were around 0.6 to 2.2 × 10^{13} L_⊙. Wang et al. (2008) observed four z ≥ 5 SDSS quasars using SHARC-II at 350 μm. They found that the warm dust temperatures were around 39–52 K, and the FIR luminosities of ~10^{13} L_⊙. Leipski et al. (2013) presented 69 QSOs at z > 5, with a mean cold component temperature of ~50 K, and a mean value of the FIR emission 10^{13} L_⊙. The mean temperature of our sample is 33 ± 5.2 K, which is cooler than the dust emission in high-redshift quasars. It seems that the host galaxies of our sample, which have z < 4, are closer to ULIRGs.

3.2.5. Revised Sample

Eight quasars, for lack of measurements at 1–10 μm, are fitted only with a power-law and a graybody. The mean temperature of the graybody is 35 ± 8.8 K. Without constraints at near- and mid-IR, their graybody temperatures are not trustworthy, thus these eight quasars are excluded from further analysis. Another 12 quasars clearly show some photometric measurement problems. For instance, the νF_ν of SDSS z is at least 10 times brighter than UKIDSS Y or 2MASS J. These quasars’ photometry need more careful examination, and therefore are also excluded from further analysis at the moment.

In the end, 207 quasars achieve good SED fitting, among them 149 are from DR7Q, and the remaining 58 are from DR10Q. They are used to calculate physical parameters in the next section. We compare the revised sample with the original sample, and they occupy the same parameter spaces in redshift and μ magnitude. Some SED fitting examples are shown in Figure 2. The result parameters along with physical parameters obtained in the next section are provided in an electronic table. The description of this electronic table is given in Table 1.

4. PHYSICAL PARAMETERS FROM SED FITTING

In this section, we discuss individual parameters estimated based on SED fitting.

4.1. Monochromatic Luminosities and Bolometric Luminosity

The monochromatic luminosities can be estimated from SED fitting. To check whether our fitting result is reasonable at UV/optical, we use DR7Q to compare L_{1350}, L_{3000}, and L_{5100} with those in Shen et al. (2011), as shown in Figure 3. In general, these two results agree very well with each other. We also see a clear tendency toward higher values in our estimates, especially for L_{1350}. It is mostly because we considered the internal extinction of quasars.

Without X-ray data, we use the bolometric luminosity correctors (BCs) provided in Shen et al. (2011) to compute the bolometric luminosity. They are BC_{5100} = 9.26 (z < 0.7), BC_{3000} = 5.15 (0.7 ≤ z < 1.9), and BC_{1350} = 3.81 (z ≥ 1.9). In
Figure 4, we compare the result using DR7Q quasars to Shen et al. (2011). Quasars with non-negligible internal extinctions are in general higher than Shen et al. (2011), while quasars with negligible internal extinctions agree with Shen et al. (2011). Overall, the bolometric luminosities given by the two methods match with each other with a mean difference of 0.20 dex. Because quasars from DR10Q do not possess bolometric luminosities from the SDSS quasar catalog DR10, we adopt bolometric luminosities from SED fitting to our entire sample for consistency. The mean bolometric luminosity of the sample, $\log (L_{\text{Bol}}/\text{erg s}^{-1})$, is 46.4 $\pm$ 0.694. Its distribution is shown in Figure 5(a).

4.2. Virial BH Mass

It is common to estimate BH masses based on single-epoch spectra. The assumption is that the broad emission line region (BLR) of an AGN is virialized. Thus, its central BH mass can be computed using the FWHM of the broad emission line (as a proxy for the virial velocity) and its corresponding continuum luminosity (as a proxy for the BLR radius). DR7Q quasars have virial BH masses from Shen et al. (2011). But DR10Q quasars only have FWHM of Mg II and C IV. We adopt the continuum luminosities from SED fitting and estimate DR7Q quasars BH masses using the Shen et al. (2011) scheme as follows:

1. if $z < 0.7,$

$$\log_{10}\left(\frac{M_{\text{BH,vir}}}{M_\odot}\right) = 0.910 + 0.50\log_{10}\left(\frac{L_{5100}}{10^{44} \text{ erg s}^{-1}}\right) + 2\log_{10}\left(\text{FWHM}(H\beta)/\text{km s}^{-1}\right)$$

(Vestergaard & Peterson 2006)

2. if $0.7 \leq z < 1.9,$

$$\log_{10}\left(\frac{M_{\text{BH,vir}}}{M_\odot}\right) = 0.740 + 0.62\log_{10}\left(\frac{L_{3000}}{10^{44} \text{ erg s}^{-1}}\right) + 2\log_{10}\left(\text{FWHM}(\text{Mg II})/\text{km s}^{-1}\right)$$

(Vestergaard & Osmer 2009)

3. if $z \geq 1.9,$

$$\log_{10}\left(\frac{M_{\text{BH,vir}}}{M_\odot}\right) = 0.660 + 0.53\log_{10}\left(\frac{L_{1350}}{10^{44} \text{ erg s}^{-1}}\right) + 2\log_{10}\left(\text{FWHM}(\text{C IV})/\text{km s}^{-1}\right)$$

(Shen & Kelly 2010).
Table 1
The SED Fitting Results: Table Description

| Column | Description |
|--------|-------------|
| 1      | Quasar index |
| 2      | Quasar designation: hhhmmss.ss+dddmmss.s (J2000.0) |
| 3      | R.A. in decimal degrees (J2000.), taken from HerS catalog |
| 4      | Decl. in decimal degrees (J2000.0), taken from HerS catalog |
| 5      | Redshift, taken from the SDSS DR7 and DR10 |
| 6      | Host galaxy fraction at 1 \( \mu m, f_g \) |
| 7      | Uncertainty in \( f_g \) |
| 8      | The internal reddening \( A_{int} \). In units of magnitude |
| 9      | Uncertainty in \( A_{int} \) |
| 10     | Host galaxy morphological type |
| 11     | FIR cold dust temperature \( T_{cold} \), in units of Kelvin |
| 12     | Uncertainty in \( T_{cold} \) |
| 13     | AGN power-law index at UV/optical \( \alpha \) |
| 14     | Uncertainty in \( \alpha \) |
| 15     | FIR luminosity integrated from 8 to 1000 \( \mu m \) Log\( L_{\text{FIR}}(\text{erg s}^{-1}) \) |
| 16     | Uncertainty in Log\( L_{\text{FIR}}(\text{erg s}^{-1}) \) |
| 17     | Bolometric luminosity Log\( L_{\text{bol}}(\text{erg s}^{-1}) \) |
| 18     | Uncertainty in Log\( L_{\text{bol}}(\text{erg s}^{-1}) \) |
| 19     | SFR Log\( (\text{SFR}(M_\odot/\text{yr})^{-1}) \) |
| 20     | Uncertainty in Log\( (\text{SFR}(M_\odot/\text{yr})^{-1}) \) |
| 21     | Monochromatic luminosity at 1300 \( \AA \), Log\( L_{1300}(\text{erg s}^{-1}) \) |
| 22     | Uncertainty in Log\( L_{1300}(\text{erg s}^{-1}) \) |
| 23     | Monochromatic luminosity at 5000 \( \AA \), Log\( L_{5000}(\text{erg s}^{-1}) \) |
| 24     | Uncertainty in Log\( L_{5000}(\text{erg s}^{-1}) \) |
| 25     | Monochromatic luminosity at 250 \( \mu m \), Log\( L_{250}\mu m(\text{erg s}^{-1}) \) |
| 26     | Uncertainty in Log\( L_{250}\mu m(\text{erg s}^{-1}) \) |
| 27     | black hole mass, Log\( (M_{\text{BH}}/M_\odot) \) |
| 28     | Gas mass, Log\( (M_{\text{gas}}/M_\odot) \) |
| 29     | Uncertainty in Log\( (M_{\text{gas}}/M_\odot) \) |
| 30     | Host galaxy mass, Log\( (M_{\text{gas}}/M_\odot) \) |
| 31     | Uncertainty in Log\( (M_{\text{gas}}/M_\odot) \) |
| 32     | Indicates which SDSS quasar catalog the object is in. |

(This table is available in its entirety in machine-readable form.)

For quasars in DR10Q, only Equations (2) and (3) are used. We combine DR7Q and DR10Q and show the BH mass distribution in Figure 5(b). The mean BH mass of our sample is 10^{8.97±0.600} M_\odot.

4.3. Host Galaxy Characteristics

After the removal of the AGN contribution, the FIR luminosity is dominated by the radiation from the young stars’ heated dust. If we assume that the dust re-radiates all of the bolometric luminosity of the starburst, the SFR can be reasonable deduced from the FIR luminosity. In this work, we compute SFR using an equation provided in Kennicutt (1998):

\[
\frac{\text{SFR}}{1 M_\odot \text{ yr}^{-1}} = \frac{L_{\text{FIR}}}{2.2 \times 10^{43} \text{ erg s}^{-1}}
\]

where \( L_{\text{FIR}} \) is FIR (i.e., the graybody component) luminosity integrated from 8 to 1000 \( \mu m \), and the Salpeter initial mass function (IMF) is assumed. As mentioned in the previous section, 93 quasars have noticeable host galaxy components, and they also contribute to star formation. Therefore, we also integrate the host component from 8 to 1000 \( \mu m \). We then adjust both SFR and \( L_{\text{FIR}} \) as the combination of the host and the graybody components. The mean SFR of our sample is 419 M_\odot yr^{-1}, slightly higher than 415 M_\odot yr^{-1} obtained without the adjustment.

For quasars with a host galaxy component, we estimate their host galaxy mass via colors. The stellar mass-to-light ratio as a function of colors can be expressed as Log\( (M/L) = a_\lambda + (b_\lambda \times \text{color}) \), where \( M/L \) ratio is in solar units. In this work, we adopt the coefficients given in Table 7 of Bell et al. (2003), while the galaxy \( g-r \) color and the \( K \) band luminosity are derived from the SED fitting. We also modified \( a_\lambda \), according to a Kennicutt IMF. The mean stellar masses are 10^{10.9} M_\odot for those quasars with early-type hosts, and 10^{10.5} M_\odot for those of late-type hosts, respectively.

In this section, we also give a rough estimate of the host galaxy gas mass. Scoville et al. (2014) states that the long-wavelength Rayleigh–Jeans (R-J) tail of dust emission is nearly always optically thin, and therefore can be used to estimate the ISM mass in galaxies, and presumably the dust emissivity per unit mass and the dust-to-gas ratio can be constrained. Equation (12) of Scoville et al. (2014) gives the flux density measurement at observed frequency \( \nu_{\text{obs}} \) as follows:

\[
S_{\nu_{\text{obs}}} (\text{mJy}) = 0.83 \frac{M_{\text{ISM}}}{10^{10} M_\odot} (1 + z)^{4.8} \left( \frac{\nu_{\text{obs}}}{\nu_{850 \mu m}} \right)^{3.8} \times \frac{\Gamma_{RJ}}{1} \left( \frac{\text{Gpc}}{d_L} \right)^2
\]

where \( M_{\text{ISM}} \) is the mass of the ISM. \( d_L \) is the luminosity distance. \( \Gamma_{RJ} \) is the correction factor for the departure from the
Note, $A_{int}$ is the internal extinction in units of magnitude, deduced from the "quasar-galaxy mixing diagram." $f_g$ is the host galaxy fraction at 1 $\mu$m, also deduced from the "quasar-galaxy mixing diagram." $\alpha$ is the AGN power-law index at UV/optical. $T_{cold}$ is the FIR cold dust temperature.

Table 2
Detailed Information for Quasars in Figure 2

| Num | Names   | Redshift | $A_{int}$ | $f_g$ | hostType | $\alpha$ | $T_{cold}$ |
|-----|---------|----------|-----------|------|----------|---------|------------|
| a   | 022031.18-010458.2 | 1.64      | 0.1 ± 0.05 | 0.0 ± 0.1 | none     | −0.09 ± 0.04 | 27.9 ± 3.00 |
| b   | 021734.63-002641.9  | 1.56      | 0.0 ± 0.0  | 0.0 ± 0.0  | none     | 0.05 ± 0.01  | 31.8 ± 3.10 |
| c   | 021857.19-004158.4  | 0.886     | 0.2 ± 0.05 | 0.4 ± 0.1  | E        | −0.2 ± 0.4   | 22.9 ± 2.42 |
| d   | 020837.95-003422.2  | 2.26      | 0.0 ± 0.04 | 0.2 ± 0.1  | E        | 0.08 ± 0.1   | 41.7 ± 6.02 |
| e   | 014648.36-002422.4  | 0.804     | 0.1 ± 0.02 | 0.1 ± 0.08 | S        | 0.04 ± 0.1   | 22.3 ± 2.30 |
| f   | 021100.99-004401.9  | 1.36      | 0.0 ± 0.0  | 0.3 ± 0.05 | S        | 0.3 ± 0.5    | 24.3 ± 2.28 |

Figure 4. Comparison of the bolometric luminosities estimated via SED fitting and from Shen et al. (2011). The dashed diagonal line denotes that the two values are equal. The data points in red represent quasars with non-negligible internal extinction, while data points in blue are quasars with negligible internal extinction. It is clear that the slightly higher values of some of our estimates are because we corrected the internal extinction.

R-J dependence as the observed emission approaches the SED peak in the rest frame; it is given by

$$
\Gamma_{RJ}(T_d, \nu_{\text{obs}}, z) = \frac{h\nu_{\text{obs}}(1+z)/kT_d}{e^{h\nu_{\text{obs}}(1+z)/kT_d} - 1}
$$

where $T_d$ is the effective dust temperature from the SED fitting, $\Gamma_0 = \Gamma_{RJ}(T_d, \nu_{\text{SSB}}, 0) = 0.71$ is a non-negligible R-J departure. Equation (5) can be only used when $\lambda_{\text{rest}} \geq 250 \mu m$. It is to ensure that the wavelength is on the R-J tail and the dust is likely to be optically thin. Scoville et al. (2014) raises cautious about using SPIRE data and the SED fitted temperature to estimate the ISM masses. They point out that, for galaxies at $z = 1 \sim 2$, SPIRE’s bandpasses will be near the FIR luminosity peak and not on the R-J tail, and thus the dust is not optically thin. In order to use Equation (5), we use the rest frame flux density at 250 $\mu$m, derived from the SED fitting and revised

Equation (5) as follows:

$$
S_{\nu_{250 \mu m}, z=0} (\text{mJy}) = \frac{0.83}{10^{10}M_\odot} \left( \frac{\nu_{250 \mu m}}{\nu_{850 \mu m}} \right)^{3.6} \times \frac{\Gamma_{RJ} \left( Gpc/d \right)}{\Gamma_0} \left( \text{Gpc} / d \right)^2
$$

(7)

where $S_{\nu_{250 \mu m}}$ is the rest frame flux density at 250 $\mu$m. The power index of the frequency ratio is changed from 3.8 to 3.6, because we used the emissivity index $\beta (= 1.6)$ through the SED fitting, instead of 1.8 as used in Scoville et al. (2014). Equation (6) is revised to

$$
\Gamma_{RJ}(T_d, \nu_{250 \mu m}, z = 0) = \frac{h\nu_{250 \mu m}/kT_d}{e^{h\nu_{250 \mu m}/kT_d} - 1}
$$

(8)

Scoville et al. (2014) points out that the flux measured near the FIR peak reflects the dust luminosity rather than its mass, and therefore the effective dust temperature derived from the observed SED might not be suitable to use for mass estimate. Taking this concern into consideration, the gas masses given in this section are very crude estimates. The mean gas mass is

$10^{11.0 \pm 0.45} M_\odot$.

5. DISCUSSIONS

We select quasars with noticeable hosts ($f_g > 0.1$) to form a subsample, denoted as HH. The remaining quasars form another subsample, denoted as HW. The summary of the entire sample and the two subsamples are listed in Table 3. Because our sample is FIR-selected, it is not surprising that the sample is biased toward gas-rich and IR-bright systems. The mean IR luminosity (integrated from 8 to 1000 $\mu$m) is $10^{12.0 \pm 0.46} L_\odot$, indicating that a great many of quasars in our sample are hosted by starbursts. The mean stellar mass is $10^{10.8 \pm 0.483} M_\odot$, similar to the stellar mass of the star-forming galaxies at $z = 1 \sim 2$ (Mullaney et al. 2012). Although the gas mass estimate in the previous section is very crude, we find that the gas mass ($M_{\text{gas}}$), the gas depletion timescales ($\tau_{\text{gas}} = M_{\text{gas}}/\text{SFR}$), and the gas mass fractions ($M_{\text{gas}}/(M_{\text{gas}} + M_\star$) are remarkably close to the values of the IR-bright sources in Scoville et al. (2014). We also find that the characteristic parameters list in Table 3 show little to no differences among the entire sample and two subsamples. The main difference between the subsamples HH and HW would be the host galaxy stellar mass. Due to the way we conduct the SED fitting, the subsample HH should only include quasars with a relatively brighter or more massive host, while quasars in HW might be relatively fainter or less massive.
times greater than when $z < 1$. Because the AGN activity and star formation are known to peak at $z \sim 2$ (e.g., Shankar et al. 2009; Behroozi et al. 2013; Burgarella et al. 2013; Delvecchio et al. 2014), we then fit the SFR as a function to the redshift within $z < 2$ and $z \geq 2$ separately. Besides the rapidly increasing SFR when $z < 2$, we also see a slight decrease toward higher redshifts at $z > 2$.

Elbaz et al. (2011) gives the redshift evolution of the star formation MS where the specific SFR of MS is $\text{sSFR}_{\text{MS}}[\text{Gyr}^{-1}] = \text{SFR}/M_{\ast} = 26 \times \tau_{\text{cosmic}}$, and $\tau_{\text{cosmic}}$ is the cosmic time elapsed since the Big Bang in Gyr. It then defines the starburst as $\text{sSFR}_{\text{SB}}[\text{Gyr}^{-1}] > 52 \times \tau_{\text{cosmic}}$, where $\text{sSFR}_{\text{SB}}$ is the specific SFR of a starburst. For subsample HH we draw their redshift versus sSFR in Figure 7. The black solid curve is the MS relation given by Elbaz et al. (2011). There are 80 quasars located above the starburst curve, which is about 38% of the entire sample. As discussed at the beginning of this section, the main difference between quasars in the subsample HH and HW is their stellar masses. It is natural to deduce that some quasars in HW have a similar SFR as those in HH, but have lower stellar masses, and thus can also fall in the starburst region. As a result, the proportion of quasars located in the starburst region should be larger than 38% for our sample. Mullaney et al. (2012) study a group of moderate-luminosity AGNs. They find that 80% of the AGNs are in star-forming systems, while only 10% are in starburst systems. The $L_\alpha$ of their sample is $10^{42} - 10^{44}$ erg s$^{-1}$. The bolometric luminosity of their sample is $10^{43.5} - 10^{45}$ erg s$^{-1}$, using the bolometric correction value of 22.4 (Mullaney et al. 2012). The mean bolometric luminosity of our sample is $10^{46}$ erg s$^{-1}$, about one magnitude higher than Mullaney et al. (2012). It seems that high-luminosity AGNs are more likely located in starburst galaxies. Previous works such as Coppin et al. (2010) also find a high percentage of moderate-to-

We draw the SFR as a function of redshift in the central plot of Figure 6. The marginal plots attached to the $x$-axis and $y$-axis are the distribution plots of the redshift and SFR, respectively. The redshift versus SFR plot shows that the SFR increases rapidly with increasing redshift. One of the possible explanations is the Malmquist bias due to the 50% completeness of the HerS catalog. We calculate the mean value of SFR at $z < 1$, $1 \leq z < 2$, and $z \geq 2$ and the relevant co-moving volume of each redshift bin. The SFR at $1 \leq z < 2$ is 3.7 times of the SFR at $z < 1$, while the SFR at $z \geq 2$ is 8.5 times of the SFR at $z < 1$. At the same time, the co-moving volume only increases about 4.2 times from when $z < 1$ to $2 \leq z < 3$. It is clear that the increase of SFR along the redshift is only partially due to the Malmquist bias. Our results are comparable to Mullaney et al. (2012), in which the SFR within $1 \leq z < 2$ bin is 3.5 times greater than within $z < 1$ bin, while the SFR when $z > 2$ is 10.3

Table 3

| Sample                        | Entire Sample | Subsample-HH | Subsample-HW |
|-------------------------------|---------------|--------------|--------------|
| Redshift LOG($L_{\text{bol}}$ (erg s$^{-1}$)) | 1.6 ± 0.77 | 1.4 ± 0.83 | 1.7 ± 0.70 |
| LOG($L_{\text{IR}}/L_{\odot}$) | 46.4 ± 0.672 | 46.2 ± 0.709 | 46.6 ± 0.587 |
| LOG($M_{\text{BH}}/M_{\odot}$) | 9.0 ± 0.60 | 8.9 ± 0.67 | 9.1 ± 0.53 |
| LOG($M_{\ast}/M_{\odot}$) | N/A | 11 ± 0.49 | N/A |
| LOG($M_{\text{gas}}/M_{\odot}$) | 11 ± 0.44 | 11 ± 0.48 | 11 ± 0.40 |
| LOG($\text{SFR}$) | 2.4 ± 0.44 | 2.4 ± 0.50 | 2.5 ± 0.38 |
| (M$_{\ast}$ (Gyr$^{-1}$)) | N/A | 0.53 ± 0.48 | N/A |
| sSFR (Gyr$^{-1}$) | 0.56 ± 0.29 | 0.64 ± 0.37 | 0.51 ± 0.18 |
| $\tau_{\text{SFR}}$ (Gyr) | N/A | 0.022 ± 0.031 | N/A |
| LOG($M_{\text{gas}}/M_{\ast}$) | N/A | 0.51 ± 0.012 | N/A |
| $M_{\text{gas}}/(M_{\ast} + M_{\text{gas}})$ | N/A | N/A | N/A |

Figure 5. (a) Distribution of the bolometric luminosity estimated via SED fitting. DR7Q is represented by dark gray, DR10Q by light gray. The dashed curve represents the entire sample. (b) Distribution of the SMBH mass computed with line luminosities from SED fitting. DR7Q is represented by dark gray, DR10Q by light gray. The dashed curve represents the entire sample.
high-luminosity AGNs (i.e., Log $L_x$ (erg s$^{-1}$) > 43.5) located above the MS. One could argue that our sample is selected based on the Herschel FIR data, which are naturally biased toward high SFR systems. In later part of this section, we will show that the AGN luminosity is indeed positively correlated to its host galaxy SFR. The lack of higher sSFR at $z > 2$ is due to the incompleteness toward the lower stellar mass quasar hosts. The lack of MS at $z < 2$ is also obvious, which is the combined effect of the lack of higher stellar mass galaxies at lower redshifts and the FIR limited sample.

For subsample HH, the mean value of $M_{\text{BH}}/M_*$ ratio is 0.02, higher than the $M_{\text{BH}}/M_{\text{bulge}}$ ratio of 0.005 in the local universe (Magorrian et al. 1998). It might indicate an evolutionary trend of the $M_{\text{BH}}-M_*$ scaling relation. There have been many studies focus on the evolution of the scaling relation. For instance, Decarli et al. (2010) studied a sample of 96 quasars with redshift up to 3 and found that the $M_{\text{BH}}/M_{\text{host}}$ ratio increases by a factor of seven from $z = 0$ to $z = 3$. Merloni et al. (2010) used 89 broad-line AGNs detected in the zCOSMOS survey in the redshift range $1 < z < 2.2$ and found that the average black hole to host galaxy mass ratio evolves positively with redshift. Bennert et al. (2011) studied 11 X-ray-selected...
broad-line AGNs in the redshift range $1 < z < 2$ and a local comparison sample of Seyfert-1 galaxies. They also found a positive relation between $M_{\text{BH}}/M_{\text{host}}$ and redshift, where $M_{\text{BH}}/M_{\text{host}, i} \propto (1 + z)^{1.15 \pm 0.15}$. The evolution of the scaling relation is expressed as

$$\log M_{\text{BH}} - 8 = \alpha (\log M_{\text{host},*} - 10) + \beta \log (1 + z) + \gamma + \sigma$$

(9)

where $\alpha = 1.12$, the slope of the relations at $z = 0$ is assumed not to evolve; $\beta = 1.15 \pm 0.15$ is used to describe the evolution of the relation; $\gamma = -0.68$ is the intercept of the relation at $z = 0$; $\sigma = 0.16 \pm 0.06$, the intrinsic scatter, is also assumed not to evolve. Using the quasars within subsample HH, we compare the $M_{\text{BH}}$ versus $M_*$ relation to AGNs in the local universe in Figure 8. The black solid line is Equation (9) at $z = 0$ with a 3σ boundary. Forty-two quasars are located above the 3σ boundary, and their BH masses are larger than those of local AGNs with the same host masses. Based on the SED fitting results, subsample HW includes 114 quasars with non-detectable hosts. It is reasonable to deduce that some quasars in subsample HW have relatively fainter hosts than those in HH; therefore, their $M_{\text{BH}}/M_*$ ratios might also be higher than those derived from Equation (9). Contrary to our results, Muller et al. (2012) find that the $M_{\text{BH}}/M_*$ of moderate luminous AGNs is $(1-2) \times 10^{-3}$, comparable to the local galaxies. It seems that the coupling between the BH accretion and the star formation is somewhat related to the AGN luminosity. The regulation of the SMBH and its host galaxy bulge has yet to be established in the host galaxy of our highly luminous quasar sample.

As discussed in the Introduction, a strong correlation between SFR and AGN activity can be found in luminous AGN systems but not in low-to-moderate-luminosity AGNs. Considering the tight relation between the SFR and $M_*$ in MS galaxies, the host galaxy stellar mass could play a role in the star formation and AGN activity relation even in galaxies beyond the MS. The galaxy gas providing fueling for both AGN accretion and star formation might also affect the evolution of these two processes. The Pearson correlation coefficient of $L_{\text{FIR}}$ versus $L_{\text{Bol}}$, $M_*$ versus $L_{\text{Bol}}$, and $M_{\text{gas}}$ versus $L_{\text{Bol}}$ are 0.70, 0.53, and 0.50, respectively, with $p$-value < 0.05. It seems that the SFR is linked more closely with the AGN activity than the stellar mass or gas mass. We plot the FIR luminosity versus AGN bolometric luminosity in Figure 9. Their correlation can be expressed as $L_{\text{FIR}} \propto L_{\text{Bol}}^{0.46 \pm 0.03}$. The Pearson correlation coefficients of individual subsample HH and HW are 0.72 and 0.68, respectively. It seems that the two subsamples follow the same relation and with the same significant level. Considering that the two subsamples share similar SFR and $L_{\text{Bol}}$ yet different $M_{\text{host}}$, it also implies a closer link between the SFR and the AGN activity than the host galaxy stellar mass. Our results might support the finding in Delvecchio et al. (2015), that the SFR is the original driver of the correlation between the star formation and the AGN activity.

6. SUMMARY

Based on the SDSS quasar catalogs, we selected a sample of galaxies that have also been observed by the Herschel Stripe 82 survey. One of the main selection criteria was that the sources have been detected by Herschel-SPIRE in all three bands. As a result, the sample is complete yet highly biased toward mid-to-far-infrared luminous objects. We conducted a full SED fitting from UV/optical to FIR. Physical parameters were calculated from SED fitting results. The main results are as follows:

1. The mean SFR is $419 M_\odot$ yr$^{-1}$ and the mean FIR luminosity is $10^{12.4} L_\odot$, similar to local massive star-forming galaxies (Kennicutt 1998). The locations of the quasar hosts on the MS diagram show that at least 26% of the quasars are hosted in starbursts.
2. The SFR increases with increasing redshift and peaks around $z = 2$. 

![Figure 8. $M_{\text{BH}}$ vs. $M_*$ evolution. The x-axis is the host galaxy stellar mass. The y-axis is the central black hole mass. The black solid line is the $M_{\text{BH}}-M_*$ scaling relation at $z = 0$ from Bennert et al. (2011). The gray area indicates the 3σ boundary. Of 93 AGNs, 42 BH masses are above the 3σ boundary, indicating an evolutionary trend.](image)

![Figure 9. AGN bolometric luminosity vs. far-infrared luminosity of the host. Quasars in the subsample HH (quasars with noticeable host) are represented in red, while quasars in the subsample HW (quasars without noticeable host) are represented in black. The solid line indicates a positive relation, where $L_{\text{FIR}} \propto L_{\text{Bol}}^{0.46 \pm 0.03}$. The quasars within subsample HH and HW follow the same $L_{\text{Bol}}$ vs. $L_{\text{FIR}}$ relation, with the same significant level.](image)
3. A positive relation between the AGN bolometric luminosity and the FIR luminosity, $L_{\text{FIR}} \propto L_{\text{bol}}^{3.46 \pm 0.03}$, is found. Studies such as Lutz et al. (2010) and Bonfield et al. (2011) also found correlations between SFR and AGN luminosity. It indicates that SFR and AGN activity are correlated in high-luminosity AGNs.

4. The AGN bolometric luminosity is also correlated with the host stellar mass and the gas mass, yet with a less significant level than the relation between $L_{\text{FIR}}$ and $L_{\text{bol}}$. It agrees with the result in Delvecchio et al. (2015), that the SFR is an original driver of the connection between the AGN activity and star formation.

5. Compared with the local universe, the higher $M_{\text{BH}}/M_{\star}$ ratio indicates an evolutionary trend of the $M_{\text{BH}}-M_{\star}$ scaling relation. It seems that in high-luminosity AGN systems, the $M_{\text{BH}}-M_{\star}$ scaling relation has yet to be established.

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