A POPULATION OF DUST-RICH QUASARS AT $z \sim 1.5$

Y. Sophia Dai, Jacqueline Bergeron, Martin Elvis, Alain Omont, Jia-Sheng Huang, Jaime Bock, Asantha Cooray, Giovanni Fazio, Evanthia Hatziminaoglou, Edo Ibata, Georgios E. Magdis, Seb J. Oliver, Mathew J. Page, Ismael Perez-Fournon, Dimitra Rigopoulou, Isaac G. Roseboom, Douglas Scott, Myrto Symeonidis, Markos Trichas, Joaquin D. Vieira, Christopher N. A. Willmer, and Michael Zemcov

1 Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA; ydai@cfa.harvard.edu
2 Boston College, 140 Commonwealth Avenue, Chestnut Hill, MA 02468, USA
3 Institut d’Astrophysique de Paris, UMR7095, 98bis Boulevard Arago, F-75014 Paris, France
4 California Institute of Technology, 1200 East California Boulevard, Pasadena, CA 91125, USA
5 Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA 91109, USA
6 Department of Physics and Astronomy, University of California, Irvine, CA 92697-4555, USA
7 ESO, Karl-Schwarzschild-Str. 2, 85748 Garching bei München, Germany
8 UK Astronomy Technology Centre, Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ, UK
9 Institute for Astronomy, University of Edinburgh, Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ, UK
10 Department of Astrophysics, Oxford University, Keble Road, Oxford OX1 3RH, UK
11 CNRS/CEA Saclay, Service d’Astrophysique Orme des Merisiers, F-91191 Gif-sur-Yvette Cedex, France
12 Astronomy Centre, Department of Physics and Astronomy, University of Sussex, Brighton BN1 9QH, UK
13 Mullard Space Science Laboratory, University College London, Holmbury St. Mary, Dorking, Surrey RH5 6NT, UK
14 Instituto de Astrofísica de Canarias (IAC), E-38200 La Laguna, Tenerife, Spain
15 Departamento de Astrofísica, Universidad de La Laguna (ULL), E-38205 La Laguna, Tenerife, Spain
16 Space Science & Technology Department, Rutherford Appleton Laboratory, Chilton, Didcot, Oxfordshire OX11 0QX, UK
17 Department of Physics and Astronomy, University of British Columbia, Vancouver, BC V6T 1Z1, Canada
18 Steward Observatory, University of Arizona, 933 North Cherry Avenue, Tucson, AZ 85721, USA

Received 2011 August 11; accepted 2012 April 27; published 2012 June 12

ABSTRACT

We report Herschel SPIRE (250, 350, and 500 $\mu$m) detections of 32 quasars with redshifts $0.5 \leq z < 3.6$ from the Herschel Multi-tiered Extragalactic Survey (HerMES). These sources are from a MIPS 24 $\mu$m flux-limited sample of 326 quasars in the Lockman Hole Field. The extensive multi-wavelength data available in the field permit construction of the rest-frame spectral energy distributions (SEDs) from ultraviolet to the mid-infrared for all sources, and to the far-infrared (FIR) for the 32 objects. Most quasars with Herschel FIR detections show dust temperatures in the range of 25–60 K, with a mean of 34 K. The FIR luminosities range from $10^{11.3}$ to $10^{13.5} L_\odot$, qualifying most of their hosts as ultra- or hyper-luminous infrared galaxies. These FIR-detected quasars appear to be a dust-rich population, but with lower redshifts and fainter luminosities than quasars observed at $z \sim 1$. However, their FIR properties cannot be predicted from shorter wavelengths (0.3–20 $\mu$m, rest frame), and the bolometric luminosities derived using the $S100$ Å index may be underestimated for these FIR-detected quasars. Regardless of redshift, we observed a decline in the relative strength of FIR luminosities for quasars with higher near-infrared luminosities.

Key words: galaxies: active – galaxies: nuclei – galaxies: starburst – infrared: galaxies – quasars: general

Online-only material: color figures

1. INTRODUCTION

The far-infrared (FIR) properties of quasars are critical for our understanding of active galaxy evolution, as they probe the possible evolutionary connection between star formation and black hole (BH) accretion (e.g., Sanders et al. 1988; Lutz et al. 2007). Both starbursts and active galactic nuclei (AGNs) could contribute to the rest-frame FIR emissions at various redshifts, although starbursts are considered to be dominant (e.g., Rowan-Robinson 1995; Trichas et al. 2009). Other models have successfully explained FIR luminosity as originating from direct AGN heating, where cool dust at large distances from the AGN reside in a warped disk/torus (e.g., Sanders et al. 1989; Haas et al. 2003). Spectral information can be used to break this degeneracy. Polycyclic aromatic hydrocarbon (PAH) features, for instance, are used to indicate star formation activity (e.g., Lutz et al. 2007). Spitzer spectroscopic studies detected PAH emission in some of the Palomar-Green (PG) and Sloan Digital Sky Survey (SDSS) quasars, where strong star formation coexists with quasars and is responsible for an average of 60% of the FIR emission (e.g., Hao et al. 2005; Netzer et al. 2007; Lutz et al. 2008; Veilleux et al. 2009; Shi et al. 2009).

Rest-frame FIR SED studies provide powerful constraints on the star formation in quasars. Despite large dispersions at different wavelengths for optically bright, unobscured quasars, their mean SEDs show surprising uniformity over redshift, luminosity, and Eddington ratio (e.g., Elvis et al. 1994, hereafter E94; Richards et al. 2006, hereafter R06; Hao et al. 2011). However, the SEDs at rest frame $\lambda > 40 \mu$m were poorly defined at high redshifts (IRAS 100 $\mu$m was the longest wavelength for E94 and R06). Several groups have tried to address this FIR gap with various sample selections (e.g., Papovich et al. 2006; Kartaltepe et al. 2010); others have taken advantage of (sub)millimeter observations, e.g., with the Infrared Space Observatory (ISO), the Institut de Radioastronomie Millimétrique (IRAM) telescope, and the Submillimetre Common-User Bolometer Array (SCUBA; e.g., Omont et al. 2001, 2003; Haas et al. 2003; Prیدdey et al. 2003a). However, a single photometric point in the rest-frame FIR, as is the case for most (sub)millimeter ((sub)mm) quasar studies, does not strongly constrain the dust
temperature distribution for these quasars. The sample sizes for (sub)mm quasars with enough photometric points that allow FIR SED studies, on the other hand, are limited due to the relatively long exposure times required for detections (e.g., Beelen et al. 2006; Wang et al. 2008, 2010). Only about 10 (sub)mm quasars reported to date have detailed rest-frame FIR SED measurements.

The Herschel19 Space Observatory (Pilbratt et al. 2010) has opened a new window (SPIRE: 250, 350, 500 μm, Griffin et al. 2010) to directly study the rest-frame FIR properties for quasars with moderate redshifts (z ∼ 1.5). The Herschel Multi-tiered Extragalactic Survey (HerMES;20 Oliver et al. 2010, 2012) covers ∼70 deg² with rich multi-wavelength data. Along with other Herschel surveys, rest-frame 30–300 μm emissions, likely due to cold dust in quasars and other AGNs, have been detected (Hatzeiminaoglou et al. 2010; Leipski et al. 2010; Serjeant et al. 2010).

In this paper, we report 32 Herschel SPIRE detections of 24 μm flux-limited quasars in the HerMES Lockman Hole field. This SPIRE-detected sample constitutes at least 10% of the 24 μm selected quasar sample in this field and allows construction of the complete FIR SEDs for these broad-line quasars at z ∼ 1.5, which triples the size of (sub)mm observed quasars that have detailed FIR SEDs. Throughout the paper, we assume a concordance cosmology with Ω_M = 0.3, and Ω_Λ = 0.7.

2. MIPS 24 μm SELECTED QUASARS AND THEIR FIR COUNTERPARTS

The quasars used in this paper are from a 24 μm flux-limited sample in the Spitzer Wide-area InfraRed Extragalactic Survey (SWIRE; Lonsdale et al. 2003). In the Lockman Hole–SWIRE (LHS) field, we selected targets that satisfy MIPS S_{24} > 0.4 mJy (~8σ), and 94% of the flux-limited sample also satisfy SDSS r_{AB} < 22.5. In 2009, J.-S. Huang et al (in preparation) performed a spectroscopic survey of ∼3000 such 24 μm targets with HECTOSPEC (Fabricant et al. 2005) on the Multiple Mirror Telescope (MMT), with an effective coverage of ~8 deg². 93% of these objects have reliable redshifts. SDSS objects with existing spectroscopic z (Hatzeiminaoglou et al. 2008) that satisfy the same flux limits were later added to the 24 μm flux-limited sample, which increased the spectroscopic completeness to ~70%. Broad-line quasars were then selected, where Mg II or C iv line width has an FWHM > 1000 km s⁻¹ (Schneider et al. 2007). The final sample of 326 24 μm selected sources includes 210 MMT and 116 SDSS quasars.

We matched these 326 quasars to the HerMES SPIRE cross-identification (XID) catalog (Roseboom et al. 2010). The XID catalog used SWIRE MIPS 24 μm positions to minimize the source blending effects due to large beam sizes (18′′ FWHM for SPIRE 250 μm images) and has a completeness of ~80% at δ_{250} = 20 mJy. Among the 326 24 μm selected quasars, there are 41 SPIRE detections with S/N > 5 of which three were detected at 350 or 500 μm only. We dropped four sources whose SPIRE 250 μm beam covers two 24 μm counterparts (e.g., Figure 1, bottom). We also excluded the five z < 0.5 objects because their rest-frame FIR data points do not constrain the SED fitting. The final sample consists of 32 quasars (20 MMT and 12 SDSS objects) at 0.50 ≤ z ≤ 3.54, with a median z of 1.55 (Figure 2, inset). This corresponds to a 10% detection rate. Since 29 of them were SPIRE 250 μm detected, the 32 quasars used in this paper are hereafter referred to as FIR-detected quasars (Figure 1, top and middle panels). Of these, 27 sources have at least one 350 or 500 μm detection (>3σ), and 16 sources also have SWIRE MIPS 70 or 160 μm detections.

3. SPECTRAL ENERGY DISTRIBUTION

We constructed the rest-frame SEDs for the 32 FIR-detected quasars from the UV to the FIR bands. The LHS field was covered by the Galaxy Evolution Explorer (GALEX) in the ultraviolet (FUV, NUV), SDSS in the optical (u, g, r, i, and z), the UKIRT Infrared Deep Sky Survey (UKIDSS) in the near-infrared (NIR; J, H, K), and the SWIRE survey in the mid-infrared (IRAC at 3.6, 4.5, 5.8, and 8.0 μm; MIPS at 24, 70, and 160 μm). A Chandra X-ray survey covered a small fraction of the LHS field (0.7 deg²), and only one source (LHS-S119) was detected out of the three FIR-detected quasars within that area (Wilkes et al. 2009). Figure 1 shows the stamp images for two FIR-detected quasars and one quasar with multiple 24 μm counterparts in the optical and infrared bands.

The rest-frame FIR emissions of these quasars fall in the 30–300 μm region, similar to those of ISO-observed PG quasars (Haas et al. 2003) and (sub)mm-detected quasars (e.g., McMahon et al. 1999; Willott et al. 2003; Priddey et al. 2003a, 2003b; Robson et al. 2004; Omont et al. 2001, 2003; Carilli et al. 2001; Beelen et al. 2006; Wang et al. 2007, 2008, 2010).

---

19 Herschel is an ESA Space Observatory with science instruments provided by European-led Principal Investigator consortia and with important participation from NASA.

20 http://hermes.sussex.ac.uk
Using the same method as was adopted in Beelen et al. (2006), we derived the dust mass $M_d$ for the FIR-detected quasars. $M_d$ is in the order of $10^8$–$10^9$ $M_{\odot}$, similar to that of (sub)mm quasars. These values are 1–2 dex higher than values estimated for the PG quasars. Therefore, these FIR-detected quasars are associated with the (sub)mm-detected quasars as a “dust-rich quasar” population (Figure 2).

In 31 out of the 32 quasars, the rest-frame SEDs exhibit FIR excess over the E94/R06 quasar templates (Section 1) by 0.5–2.3 dex at 90 $\mu$m, with an average of 1.4 dex. This suggests that the contribution from cool dust is present. We compared the mean SEDs for FIR-detected and the much larger sample of undetected quasars (Figure 3). These mean SEDs were constructed by combining individual rest-frame SEDs. We first converted the flux densities to luminosities for each object. After shifting their bandpasses to the rest frame, we estimated by first cutting out maps around the MIPS 24 $\mu$m positions for individual sources (interpolation into sub-pixels was allowed for precisely centering), and then measured from the stacked map via a centered point-spread function (PSF) fitting. Errors associated with the mean fluxes were calculated using the bootstrap method. SEDs for both populations resemble the R06/E94 templates in the optical and the NIR, and differ mainly in the FIR: the stacked $S_{250}$ for FIR-detected sources is $\sim$ 8 mJy, about 4 times lower than the median $S_{250}$ for FIR-detected quasars (31.1 mJy). UV–optical reddening is common in both populations, being present in $\sim$40% of the FIR-detected quasars. The reddening corrections are complicated (Hao et al. 2005) and beyond the scope of this paper, as we concentrate on the FIR.

### 3.1. Modeling the FIR Quasar SED

For this work, we adopted a $T$–$\alpha$–$\beta$ model from Blain et al. (2003) to estimate the dust temperatures and quasar luminosities. Different from a pure modified blackbody (MBB) model, which uses an exponential thermal function with emissivity index $\beta$ to account for a single-temperature dust component, the $T$–$\alpha$–$\beta$ model, a power-law Wien tail ($f_\nu \propto \nu^{-\alpha} B_{\nu, \beta}$) is introduced to the mid-IR SED to account for the warmer dust components (Figure 4). This additional term is then matched to the MBB component at a transition point, where the two functions also have equal first-order derivatives. This transition wavelength varies from case to case. We adopted $\beta = 2.0$ here (Priddey et al. 2003a). At shorter wavelengths, we normalized the R06 template to each SED over the 1–5 $\mu$m range for reference.

Out of the 32 quasars, only 4 have a single-band rest-frame FIR detection. One (LHS-M020) of the four sources matches well to the R06 template in the optical and near infrared bands.

---

21. $M_d = S_\nu B_\nu / (1+z) k_d(\nu) B(\nu, T_d)$, where $k_d(\nu) = k_0(\nu/\nu_0)^\beta$ is the dust absorption coefficient. Here we used $S_{250}$, and $k_0$ is from Alton et al. (2004).

22. $f_\nu \propto \nu^{\beta} B_{\nu, \beta}$, where $B_{\nu, \beta}$ is the blackbody spectrum.

23. A change in $\beta$ from 2.0 to 1.5 does not significantly ($<3\sigma$) change the fitted $T_d$ and the $L_{\text{IR}}$ (see also Section 3.2). Since real dust may have a temperature distribution, the fitted temperature only applies to the cold dust component defined by the rest-frame FIR data, while the fitted $\alpha$ term indicates the relative strength of warm and hot dust.
The quasar with the highest $z$, LHS–M268, also has an SED that is well described by the R06 template alone (within 0.2 dex in the FIR). So no fit was attempted for these five objects.

We carried out $T\alpha$–$\beta$ fits to the remaining 27 SEDs of which 9 objects have all 3 SPIRE detections. Longward of the Lyman break (912 Å), 22 quasars are well described by the R06 template and a $T\alpha$–$\beta$ fit. All 12 SDSS quasars fall into this category. The remaining five less-well-defined SEDs show a strong stellar bump in the optical–NIR regime, presumably from the host galaxy, while their FIR SEDs are well described by a $T\alpha$–$\beta$ fit. Figure 4 presents the individual SED for each of the 32 FIR-detected quasars. The plots are labeled with their ID, redshift, fitted dust temperature, and $\alpha$, and follow an $\alpha$ decreasing order to match Table 1. No host-galaxy correction was applied.

### 3.2. Dust Temperatures and Luminosities

The fitted dust temperature ($T_d$) for these 27 quasars has a range of 18–80 K, with 87% of the sources in the range of 25–60 K, and a median and mean of 29 K and 34 K (Figure 5, right). The fitting error for $T_d$ is less than 10% in $\sim$70% of the cases. However, it is worth noting that $T_d$ derived from $T\alpha$–$\beta$ fit is on average 30% lower than that from a pure MBB fit, where no power-law term is present. The FIR luminosities are similar within 3σ between these two fits.

The fitted $\alpha$ for these 27 sources has a wide range of 0.68–2.44 (Table 1). Starburst sources are found to have higher $\alpha$ values than normal star-forming galaxies and quasars, as was shown in Blain et al. (2003). Different $\alpha$ values suggest different dust temperature compositions in individual quasar systems and may be associated with different evolutionary stages: flatter slopes ($\alpha < 1.0$) imply infrared SEDs with relatively stronger warmer dust emissions, likely heated directly by the quasar; while steeper slopes ($\alpha > 2.0$) indicate a colder dust-dominant infrared SED, similar to that of star-forming galaxies (Figure 5, left). A majority of the 27 quasars ($\sim$70%) have an $\alpha$ value of $1.0 \leq \alpha \leq 2.0$, possibly in a mixed condition between the two extremes.

The FIR luminosities $L_{\text{FIR}}$ (40–300 μm) were estimated by integrating over the fitted SEDs, while the total infrared luminosities $L_{\text{IR}}$ (8–1000 μm) (Kennicutt 1998) were integrated over the observed SEDs up to the redshifted MIPS 24 μm data.
and over the fitted SEDs at longer wavelengths. $L_{\text{FIR}}$ ranges from $10^{11.3}$ to $10^{13.5} L_\odot$, while $L_\text{IR}$ has a range of $10^{14.5}$ to $10^{14.3} L_\odot$, qualifying most of their host galaxies as ultra- or hyper-luminous infrared galaxies (ULIRGs, $L_{\text{IR}} > 10^{12} L_\odot$; HyLIRGs, $L_{\text{IR}} > 10^{13} L_\odot$; Sanders & Mirabel 1996): in the 27 quasars with a $T-\alpha-\beta$ fit, there are 8 ULIRGs and 13 HyLIRGs. Of the 27 quasars, 21 have $L_{\text{FIR}}/L_{\text{IR}} > 0.2$, and 16 show $L_{\text{FIR}}/L_{\text{IR}} > 0.5$, indicating major contributions from the FIR to the total $L_\text{IR}$. For FIR-undetected quasars, this ratio is $\sim 0.3$ based on their mean SED (Figure 3). We also estimated the “big blue bump” luminosity, $L_{\text{BB}}$ (0.1–0.4 $\mu$m), and the near-infrared luminosity, $L_{\text{NIR}}$ (2–10 $\mu$m), by integrating over the observed SEDs for all quasars. The 2–10 $\mu$m range was chosen to minimize the stellar contribution and to better represent the “hot dust bump” emission likely to be directly heated by the quasar (Wang et al. 2008). These integration ranges can be found in Figure 3 as shaded regions. The parameters used and derived from the SEDs are summarized in Table 1 (see also Figure 5). Errors for $T_d$, $\alpha$, $L_{\text{FIR}}$, and $L_{\text{IR}}$ are fitting errors only. The errors for $L_{\text{BB}}$ and $L_{\text{NIR}}$ contain only the photometric errors and are not listed in Table 1 because of their small values: mostly at the 1% level or less for $L_{\text{BB}}$ and at most a few percent for $L_{\text{NIR}}$.

The FIR-detected and undetected quasars have similar $L_{\text{BB}}$ and $L_{\text{NIR}}$ values and distributions, with $L_{\text{NIR}} \sim 25\%$ higher for FIR-detected quasars at higher redshifts (Figure 6, left). The $L_{\text{FIR}}/L_{\text{NIR}}$ ratio, however, shows an obvious excess over the E94 template range, especially at $L_{\text{NIR}} \lesssim 10^{13} L_\odot$ (Figure 6, right). We also plot the mean $L_{\text{FIR}}/L_{\text{NIR}}$ ratios for FIR-undetected quasars in three $L_{\text{NIR}}$ bins. These values were derived from the mean SEDs at each $L_{\text{NIR}}$ bin in the $1 < z < 2$ range (covering the mean $z$ of $\sim 1.5$), assuming $\beta = 2.0$ and $\alpha = 1.6$ (mean for FIR-detected quasars). These SEDs were completed in the FIR using the stacked fluxes from the SPIRE images for the relevant FIR-undetected sources. For comparison, FIR-detected quasars in the same redshift range are marked with a cross in the center.

It is clear that at the same redshift ($1 < z < 2$ in this case) and luminosity bins, FIR-detected quasars have higher $L_{\text{FIR}}/L_{\text{NIR}}$ ratios than FIR-undetected objects, indicating differences in $M_d$, $T_d$, or AGN activities. This ratio seems to decrease at higher $L_{\text{NIR}}$ regardless of redshift, though the large scatter at $L_{\text{NIR}} < 10^{13} L_\odot$ prevents determination of a tight correlation. The quasars’ FIR properties cannot be predicted from shorter wavelengths, given the similar SED shapes and luminosities between FIR-detected and undetected quasars at optical and near-infrared regions (Figure 6, left). Considering this similarity and the common UV extinctions, no bolometric luminosity was calculated for the FIR-detected quasars.

4. DISCUSSION

We constructed a sample of 32 quasars ($0.5 < z < 3.6$) with Herschel SPIRE detections, which triples the size of (sub)mm-observed quasars that have detailed FIR SEDs. These FIR-detected quasars, as well as some FIR-undetected quasars in our sample (Figure 3), show broad-line features and strong cold dust emissions simultaneously. This is inconsistent with the evolutionary scenario that naked quasars are only seen when the dust has been blown out (e.g., Haas et al. 2003). The dust detected by Herschel shows temperatures from 18 K to 80 K (Section 3.2), with 87% of the sources in a range of 25–60 K. Similar to local and $z \sim 2$ starburst galaxies and ULIRGs (20 K < $T_d$ < 60 K) (Calzetti et al. 2000; Magdis et al. 2010). The median and mean $T_d$ in our sample are 29 K and 34 K, respectively. Since the FIR emissions for these FIR-detected and the (sub)mm-detected quasars (e.g., Omont et al. 2001, 2003; Carilli et al. 2001; Beelen et al. 2006) both fall in the rest-frame 30–300 $\mu$m region, we associated these two populations as a “dust-rich quasar” population (Figure 2). Estimated dust mass confirmed this connection (see also Section 3). ISO-detected quasars (Haas et al. 2003) are possibly at the low-$z$ end of this population, though their $M_d$ could be 1–2 dex lower. A common assumption is that the dust-rich quasars are in transition between optically obscured and unobscured quasar phases, but near-infrared/(sub)mm spectroscopy and high-resolution images are needed to test this.

At shorter wavelengths (rest-frame 0.3–20 $\mu$m), the FIR-detected and undetected quasars have similar mean SEDs (Figure 3), redshift (Figure 2, inset), and luminosity distributions (Figure 6, left). $L_{\text{NIR}}$ is $\sim 25\%$ higher for the FIR-detected population, likely affected by their FIR excess. The lack of correlation between properties at the FIR and shorter wavelengths tests the widely used conversion factor of 7 between $L_{\text{S}1000}$ Â and $L_{\text{bol}}$ for AGNs and quasars (Shemmer et al. 2004). For these FIR-detected bright-line quasars ($\sim 10\%$ of the flux-limited sample), if the rest-frame FIR emission is mainly due to quasar heating, this factor should be modified to 9–20 based on the $L_{\text{FIR}}/L_{\text{IR}}$ ratio. Whether this applies to the flux-limited quasar population in general remains to be investigated.
Figure 4. Individual rest-frame SEDs for the FIR-detected quasars in our sample, with energy $\lambda L_\lambda$ in $L_\odot$. The SEDs were constructed with existing data from the UV to the mid-infrared, complemented in the FIR by the HerMES-SPIRE observations (see Figure 3 for details). The red curves plot a $T-\alpha-\beta$ fit with $\beta = 2.0$, with fitted $T_d$ and $\alpha$ given in the legend, and blue curves are the R06 template normalized at 1–5 $\mu$m. The parameters are summarized in Table 1. The objects are arranged in an $\alpha$ decreasing order and followed by quasars with special SED shapes. No host-galaxy correction was applied.

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

At $1 < z < 2$, the $L_{\text{FIR}}/L_{\text{NIR}}$ ratios for FIR-detected quasars are on average 2× higher than FIR-undetected ones. $L_{\text{FIR}}/L_{\text{NIR}}$ and $L_{\text{NIR}}$ seem to be anti-correlated (Figure 6, right). This trend is also observed for the overall population despite the large scatter at $L_{\text{NIR}} < 10^{13} L_\odot$: the relative strength of $L_{\text{FIR}}$, commonly associated with star formation (e.g., Lutz et al. 2007), decreases at higher $L_{\text{NIR}}$, indicator of warm dust partially or mostly heated by AGNs. This trend is consistent with the assumption that star formation is suppressed by the presence of a powerful AGN (Hopkins et al. 2006).

Both star-forming galaxies and AGNs may contribute to the rest-frame FIR emission at various redshifts. If we attribute the FIR luminosity to star formation, as was adopted in some previous studies (e.g., Evans et al. 2006; Riechers et al. 2006; Netzer et al. 2007; Wang et al. 2010, 2011), about 40% of the sample will require a star formation rate (SFR) $> 100 M_\odot$ yr$^{-1}$, similar to that of submillimeter galaxies (e.g., Lutz et al. 2008).

24 Equation (4) in Kennicutt (1998): $\text{SFR} (M_\odot \text{yr}^{-1}) = 1.7 \times 10^{-10} L_{\text{IR}}(L_\odot)$. Here we used $L_{\lambda=850}^{\text{FIR}}$ instead of $L_{\lambda=1000}^{\text{FIR}}$ for a more conservative estimate that reduces further contamination from the AGN.
Figure 4. (Continued)

Figure 5. Histograms of the fitted power-law slope $\alpha$ (left) and the dust temperature $T_d$ (right) for the FIR-detected quasars.
However, for the high-luminosity end \((L_{\text{NIR}} \geq 3 \times 10^{13} L_\odot)\), Figure 6, with only one source, the statistics are insufficient to prove whether there is a similar proportion of starburst-dominated quasars, as was found for (sub)mm-observed quasars (i.e., ~20%–30%; Wang et al. 2008).

On the other hand, for some quasars, the SFR derived from \(L_{\text{FIR}}\) reaches 5000 \(M_\odot\) yr\(^{-1}\), which is unlikely and probably implies that part of the FIR emission is powered by AGNs. In Figure 6 (right), we found that for the more luminous quasars \((L_{\text{NIR}} > 5 \times 10^{12} L_\odot)\), the \(L_{\text{FIR}}/L_{\text{NIR}}\) ratio falls in the normal quasar range, suggesting pure quasar heating. Resolved CO and PAH emission from NIR/millimeter spectroscopy and high-resolution imaging showing dust distribution will provide a better estimate of the relative contributions from AGNs and starbursts for these dust-rich quasars.

This research has made use of data from the HerMES project—a Herschel Key Program utilizing Guaranteed Time from the SPIRE instrument team, ESA scientists and a mission scientist. SPIRE has been developed by a consortium of institutes led by Cardiff University (UK) and including the University of Lethbridge (Canada); NAOC (China); CEA, LAM (France); IFSI, the University of Padua (Italy); IAC (Spain); Stockholm Observatory (Sweden); Imperial College London, RAL, UCL-MSSL, UKATC, the University of Sussex (UK); Caltech, JPL, NHSC, the University of Colorado (USA). This development has been supported by national funding agencies: CSA (Canada); NAOC (China); CEA, CNES, CNRS (France); ASI (Italy); MCINN (Spain); SNSB (Sweden); STFC and UKSA (UK); and NASA (USA). The HerMES data were accessed through the HeDaM database (http://hedam.oamp.fr) operated by CeSAM and hosted by the Laboratoire d’Astrophysique de Marseille. We acknowledge support from the Science and Technology Facilities Council (grant numbers ST/F002858/1 and ST/I000976/1). This work is based partly on observations made with the Spitzer Space Telescope and the MMT Observatory, operated by the Jet Propulsion Laboratory, Caltech under a contract with NASA, and the Smithsonian Astrophysical Observatory and the University of Arizona, respectively. Research by Y. S. D. is supported by the SAO Predoctoral Fellowship.

**Facilities:** Herschel, MMT, Spitzer

### REFERENCES

Alton, P. B., Xilouris, E. M., Misiriotis, A., Dasyra, K. M., & Dunke, M. 2004, A&A, 425, 109

Beelen, A., Cox, P., Benford, D. J., et al. 2006, ApJ, 642, 694

Blain, A. W., Barnard, V. E., & Chapman, S. C. 2003, MNRAS, 338, 733

Calzetti, D., Armus, L., Bohlin, R. C., et al. 2000, ApJ, 533, 682

Carilli, C. L., Bertoldi, F., Rupen, M. P., et al. 2001, ApJ, 555, 625

Elvis, M., Wilkes, B. J., McDowell, J. C., et al. 1994, ApJS, 91, 5

Evans, A. S., Solomon, P. M., Tacconi, L. J., Vavilkin, T., & Downes, D. 2006, AJ, 132, 2398

Fabricant, D., Fata, R., Roll, J., et al. 2005, PASP, 117, 1411

Griffin, M. J., Abergel, A., Abreu, et al. 2010, A&A, 518, L3

Haas, M., Klaas, U., Müller, S. A. H., et al. 2003, A&A, 402, 87

Hao, H., Elvis, M., Civano, F., & Lawrence, A. 2011, ApJ, 733, 108

Hao, L., Strauss, M. A., Fan, X., et al. 2005, AJ, 129, 1795

Hatziminaoglou, E., Fritz, J., Franceschini, A., et al. 2008, MNRAS, 386, 1252

Hatziminaoglou, E., Omont, A., Stevens, J. A., et al. 2010, A&A, 518, L33

Hopkins, P. F., Hernquist, L., Cox, T. J., et al. 2006, ApJS, 163, 1

Kartaltepe, J. S., Sanders, D. B., Le Floc’h, E., et al. 2010, ApJ, 709, 572

Kennicutt, R. C., Jr. 1998, ARA&A, 36, 189

Leipski, C., Meisenheimer, K., Klaas, U., et al. 2010, A&A, 518, L34

Lonsdale, C. J., Smith, H. E., Rowan-Robinson, M., et al. 2003, PASP, 115, 897

Lutz, D., Sturm, E., Tacconi, L. J., et al. 2007, ApJ, 661, L25

Lutz, D., Sturm, E., Tacconi, L. J., et al. 2008, ApJ, 684, 853

Magdis, G. E., Elbaz, D., Hwang, H. S., et al. 2010, MNRAS, 409, 22

McMahon, R. G., Priddey, R. S., Omont, A., Snellen, I., & Withington, S. 1999, MNRAS, 309, L1

Netzer, H., Lutz, D., Schweitzer, M., et al. 2007, ApJ, 666, 808

Oliver, S. J., Wang, L., Smith, A. J., et al. 2010, A&A, 518, L21

Oliver, S. J., Brock, J., Altieri, B., et al. 2012, MNRAS, arXiv:1203.2562

Omont, A., Beelen, A., Bertoldi, F., et al. 2003, A&A, 398, 857

Omont, A., Cox, P., Bertoldi, F., et al. 2001, A&A, 374, 371

Papovich, C., Cool, R., Eisenstein, D., et al. 2006, AJ, 132, 231

Pilbratt, G. L., Riedinger, J. R., Passvogel, T., et al. 2010, A&A, 518, L1

Priddey, R. S., Isaak, K. G., McMahon, R. G., Robson, E. I., & Pearson, C. P. 2003, MNRAS, 344, L74

![Figure 6. Left: ratio between the near-infrared and the “big blue bump” luminosities (definitions in Section 3.2 and Figure 4, left). Hatched area marks the E94-predicted range (90% confidence; E94 was used since R06 template stops at rest-frame 100 μm). Right: the relation between FIR and NIR luminosities for FIR-detected quasars. Eleven FIR-detected sources have a higher ratio than the E94 prediction. Significant higher range (90% confidence; E94 was used since R06 template stops at rest-frame 100 μm). Large black crosses are the mean \(L_{\text{FIR}}/L_{\text{NIR}}\) ratios for FIR-detected quasars at \(1 < z < 2\) in each \(L_{\text{NIR}}\) bin. FIR-detected quasars of the same redshift range are marked with a small cross at the center.](http://hedam.oamp.fr)
Richards, G. T., Lacy, M., Storrie-Lombardi, L. J., et al. 2006, ApJS, 166, 470
Riechers, D. A., Walter, F., Carilli, C. L., et al. 2006, ApJ, 650, 604
Robson, I., Priddey, R. S., Isaak, K. G., & McMahon, R. G. 2004, MNRAS, 351, L29
Roseboom, I. G., Oliver, S. J., Kunz, M., et al. 2010, MNRAS, 409, 48
Rowan-Robinson, M. 1995, MNRAS, 272, 737
Sanders, D. B., & Mirabel, I. F. 1996, ARA&A, 34, 749
Sanders, D. B., Phinney, E. S., Neugebauer, G., Soifer, B. T., & Matthews, K. 1989, ApJ, 347, 29
Sanders, D. B., Soifer, B. T., Elias, J. H., et al. 1988, ApJ, 325, 74
Schneider, D. P., Hall, P. B., Richards, G. T., et al. 2007, AJ, 134, 102
Serjeant, S., Bertoldi, F., Blain, A. W., et al. 2010, A&A, 518, L7
Shemmer, O., Netzer, H., Maiolino, R., et al. 2004, ApJ, 614, 547
Shi, Y., Rieke, G. H., Ogle, P., Jiang, L., & Diamond-Stanic, A. M. 2009, ApJ, 703, 1107
Trichas, M., Georgakakis, A., Rowan-Robinson, M., et al. 2009, MNRAS, 399, 663
Veilleux, S., Rupke, D. S. N., Kim, D.-C., et al. 2009, ApJS, 182, 628
Wang, R., Carilli, C. L., Neri, R., et al. 2010, ApJ, 714, 699
Wang, R., Carilli, C. L., Beelen, A., et al. 2007, AJ, 134, 617
Wang, R., Carilli, C. L., Wagg, J., et al. 2008, ApJ, 687, 848
Wang, R., Wagg, J., Carilli, C. L., et al. 2011, AJ, 142, 101
Wilkes, B. J., Kilgard, R., Kim, D.-W., et al. 2009, ApJS, 185, 433
Willott, C. J., Rawlings, S., & Grimes, J. A. 2003, ApJ, 598, 909