COMPLETE INFRARED SPECTRAL ENERGY DISTRIBUTIONS
OF MILLIMETER DETECTED QUASARS AT $z > 5$

C. Leipski$^1$, K. Meisenheimer$^1$, F. Walter$^1$, M.-A. Besel$^1$, H. Dannerbauer$^2$, X. Fan$^3$, M. Haas$^4$, U. Klaas$^1$, O. Krause$^1$, and H.-W. Rix$^1$

1 Max-Planck Institut für Astronomie (MPIA), Königstuhl 17, D-69117 Heidelberg, Germany; leipski@mpia-hd.mpg.de
2 Institut für Astrophysik, Universität Wien, Türkenschanzstraße 17, A-1180 Wien, Austria
3 Steward Observatory, University of Arizona, Tucson, AZ 85721, USA
4 Astronomisches Institut Ruhr-Universität Bochum, Universitätstraße 150, D-44801 Bochum, Germany

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ABSTRACT

We present Herschel far-infrared (FIR) photometry of 11 quasars at redshift $z > 5$ that have previously been detected at 1.2 mm. We perform full spectral energy distribution (SED) fits over the wavelength range $\lambda_{\text{rest}} \sim 0.1-400 \mu m$ for those objects with good Herschel detections. These fits reveal the need for an additional FIR component besides the emission from a dusty active galactic nucleus (AGN)-powered torus. This additional FIR component has temperatures of $T_{\text{FIR}} \sim 40-60$ K with luminosities of $L_{8-1000 \mu m} \sim 10^{13} L_{\odot}$ (accounting for 25–60% of the bolometric FIR luminosity). If the FIR dust emission is due to star formation it would suggest star formation rates in excess of 1000 solar masses per year. We show that at long wavelengths ($\lambda_{\text{rest}} \gtrsim 50 \mu m$) the contribution of the AGN-powered torus emission is negligible. This explains how previous FIR studies of high-redshift quasars that relied on single-component fits to (ground-based) observations at $\lambda_{\text{obs}} \gtrsim 350 \mu m$ reached $T_{\text{FIR}}$ and $L_{\text{FIR}}$ values similar to our complete SED fits. Stacking the Herschel data of four individually undetected sources reveals a significant average signal in the PACS bands but not in SPIRE. The average SED of sources with individual Herschel detections shows a striking surplus in near- and mid-infrared (MIR) emission when compared to common AGN templates. The comparison between two average SEDs (sources with and without individual Herschel detections) matched in the UV/optical indicates that for these objects the strength of the MIR emission may correlate with the strength of the FIR emission.

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

Online-only material: color figures

1. INTRODUCTION

The presence of dust seems to be a ubiquitous property of galaxies throughout the observable universe. Even the most distant quasars at $z \sim 6$ show evidence for copious amounts of dust (e.g., Bertoldi et al. 2003; Beelen et al. 2004; Wang et al. 2003a; Leipski et al. 2010b). This indicates rapid metal enrichment of the interstellar medium within the first billion years after the big bang. About 30% of the known luminous $z \sim 6$ quasars are detected in the millimeter continuum with many of them also detected in CO (e.g., Wang et al. 2003a, and references therein). Such studies confirm the notion that most of the rest frame far-infrared (FIR) emission comes from massive star formation, possibly indicating the formation of early galactic bulges. Thus, these objects signify an important stage in the connection between the build-up of stellar mass and black hole growth.

Most high-redshift objects lack full FIR/submillimeter spectral energy distributions (SEDs). $L_{\text{FIR}}$ and $M_{\text{dust}}$ are commonly determined using single photometric measurements, typically obtained at 1.2 mm ($\approx 250$ GHz) and applying standard values for the dust temperature as determined from lower redshift objects. It is unknown whether this assumption is appropriate for high-redshift objects. Ground-based 350 $\mu m$ observations of a few $z > 5$ quasars tentatively support the assumed values for the dust temperatures when combined with further submillimeter and millimeter data (Wang et al. 2003b).

For a more comprehensive picture of the dust emission at high redshifts we have obtained Photodetector Array Camera and Spectrometer (PACS, 100 + 160 $\mu m$) and Spectral and Photometric Imaging Receiver (SPIRE, 250 + 350 + 500 $\mu m$) photometry of 69 quasars at $z > 5$ as part of our Herschel Space Observatory (Pilbratt et al. 2010) key project “The Dusty Young Universe.” Spitzer Space Telescope (Werner et al. 2004) observations complement these data. This enables the study of the full optical through infrared SED of these objects in the rest frame wavelength range 0.5–80 $\mu m$, which—most importantly—covers the FIR peak of the SED. While the photometry for the complete key project sample will be presented in a forthcoming paper, we here report on the Herschel observations and SED analysis of the 11 objects in the sample which were previously detected at 1.2 mm (Table 1). Currently, this sub-sample is best suited to explore the relative importance of FIR and submillimeter/millimeter measurements for the interpretation of the total infrared SED and the contribution from the coolest dust components. Moreover, the increased wavelength coverage allows us to develop our fitting procedure with optimal constraints.

We outline the data reduction in Section 2. In Section 3 we describe how we extract physical properties from our measurements, which are then discussed in Section 4. We summarize and conclude in Section 5. Throughout the paper we use a $\Lambda$CDM cosmology with $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.27$, and $\Omega_\Lambda = 0.73$.

$^5$ Herschel is an ESA space observatory with science instruments provided by European-led Principal Investigator consortia and with important participation from NASA.
We each object.

This resulted in a total on-source integration time of a few minutes. Data reduction was performed within the Herschel Interactive Processing Environment (HIPE; Ott 2010), version 8.0.1. We followed standard procedures for deep field data reduction, including source masking and high-pass filtering. The maps of the two scan directions were processed individually and mosaicked at the end of the work flow. A first version of the mosaics was then performed, including the mask. The distribution of the measured fluxes in these 500 apertures was then fitted by a Gaussian. The sigma value of this Gaussian was taken as the 1σ photometric uncertainty of this map. The resulting flux values for the quasars are given in Table 2.

2.2. SPIRE

All quasars in the sample were also observed with the SPIRE (Griffin et al. 2010) at 250, 350, and 500 μm in small scan map mode for five repetitions and a total on-source integration time of ~190 s per source. Data reduction followed standard procedures in HIPE as recommended by the SPIRE instrument team. Source extraction was performed with the HIPE built-in task “sourceExtractorSussextractor” (Savage & Oliver 2007) using information on the PSF (e.g., FWHM) given in the SPIRE Observer’s Manual.8

Our observations are dominated by confusion noise which is on the order of 6–7 mJy beam$^{-1}$ in the SPIRE photometric bands (Nguyen et al. 2010) as determined from deep extragalactic fields. In order to estimate the uncertainties due to confusion noise specifically in our target fields, we implemented the following procedure (see also Elbaz et al. 2011; Pascale et al. 2011). First, the source extractor was run over the full calibrated data. Detections within less than half the FWHM from the nominal target position were tentatively considered to belong to the quasar, pending further confirmation from our check for confusion with nearby FIR bright sources. We then created an artificial image which included all the sources found by the source extractor and subtracted this “source image” from the observed map. On this “residual map” we determined the pixel-to-pixel rms in a box with a size of 8 times the FWHM (FWHM size: 18′′/2, 24′′/9, and 36′′/3 for default map pixel sizes of 6′′, 10′′, and 14′′ at 250, 350, and 500 μm, respectively), centered on the nominal position of the QSO. The size of this box was chosen large enough to allow an appropriate sampling of the surroundings of the source, but small enough to avoid including the lower coverage areas at the edges of the map even for the longest wavelengths. In addition, the number of pixels per FWHM is approximately constant for the three wavelengths in the final maps (2.5–3.0 pixel FWHM$^{-1}$) which translates into a similar number of pixels used for determining the rms in the background box. The resulting estimates for the noise (limited by confusion) are comparable to the average values given in Nguyen et al. (2010), but have a tendency to be slightly lower. The fluxes and uncertainties we determine are given in Table 2 and the 250 μm maps are presented in Figure 1.

We note that Table 2 lists a number of SPIRE flux measurements which are nominally below the estimated 3σ value of the noise. In these cases, the inspection of the images revealed a

| Name            | Redshift | $m_{1450}$ (mag) | $f_{250}$ (mJy) | References |
|-----------------|----------|-----------------|-----------------|------------|
| J020332.35+001228.6 | 5.72     | 20.94           | 1.85 ± 0.46     | 1, 2       |
| J033829.30+002156.2 | 5.03     | 20.01           | 3.7 ± 0.3       | 4, 5       |
| J075618.13+10408.5  | 5.11     | 20.15           | 5.5 ± 0.5       | 6, 7       |
| J081827.40+172251.8 | 6.00     | 19.34           | 1.19 ± 0.38     | 8, 3       |
| J084035.09+562419.9 | 5.84     | 20.04           | 3.20 ± 0.64     | 8, 9       |
| J092721.82+200123.7 | 5.77     | 19.87           | 4.98 ± 0.75     | 8, 3       |
| J104433.04−012502.2 | 5.78     | 19.21           | 1.82 ± 0.43     | 10, 3      |
| J104845.05+463718.3 | 6.23     | 19.25           | 3.0 ± 0.4       | 11, 12     |
| J114186.64+525150.2 | 6.42     | 19.03           | 5.0 ± 0.6       | 11, 12     |
| J133550.80+353315.8 | 5.90     | 19.89           | 3.34 ± 0.50     | 8, 9       |
| J205406.42−000514.8 | 6.04     | 20.60           | 2.38 ± 0.53     | 1, 3       |

Notes. (1) SDSS name ordered by R.A.; (2) redshift confirmed by CO measurements or NIR spectroscopy where available (see the Appendix); (3) apparent AB magnitude at 1450 Å in the rest frame of the quasar, corrected for galactic extinction; (4) observed 250 GHz flux in mJy. Errors are 1σ; (5) references for Columns 3 and 4, respectively.

References. (1) Jiang et al. 2008; (2) Wang et al. 2011; (3) Wang et al. 2008a; (4) Fan et al. 1999; (5) Carilli et al. 2001; (6) Wang et al. 2008b; (7) Petric et al. 2003; (8) Fan et al. 2006; (9) Wang et al. 2007; (10) Fan et al. 2001; (11) Fan et al. 2003; (12) Bertoldi et al. 2003.
clear excess of flux at the position of the quasar. It has been shown that the use of positional priors can reduce the effect of confusion noise by 20%–30% (Roseboom et al. 2010). While our strategy is somewhat different from that work, we benefit not only from accurate (relative and absolute) positional information, but also from information on the SEDs of the quasar and potential confusing sources in the field via our multi-wavelength data. This leads us to include these flux measurements in this study, although they have to be treated with caution. Similarly, fluxes at 500 μm should be considered tentative because at this wavelength the beam is large (∼36′′ FWHM), the confusion noise is high, and the significance of the detections is often low.

2.3. Spitzer

For all Herschel targets (except J2054−0005) we also have available mid-infrared (MIR) imaging from Spitzer at 3.6, 4.5, 5.8, and 8.0 μm with the InfraRed Array Camera (IRAC; Fazio et al. 2004) as well as at 24 μm with the Multiband Imaging Photometer for Spitzer (MIPS; Rieke et al. 2004). For the

Figure 1. The final maps of the quasars at 24, 100, 160, and 250 μm (from left to right). All images are 2′ on a side and north is to the top with east to the left. The circle indicating the position of the quasar has a diameter of 20′′. Sources detected in a particular band have their source name underlined in the corresponding image. In the case of J0818+1722 the bright source close to the QSO position at 100, 160, and 250 μm is identified with a foreground object. The QSO itself is undetected at these wavelengths (see the Appendix for details). (A color version of this figure is available in the online journal.)
redshifts of our sources these passbands cover the rest frame optical and near-infrared (NIR) wavelengths (\(\sim 0.5–4 \mu m\)). The Spitzer data have been processed using standard procedures within the Mopex software package provided by the Spitzer Science Center (SSC). Aperture photometry was performed in IDL using standard sets of aperture radii and appropriate aperture corrections as outlined in the respective instrument handbooks (also available from the SSC Web site). Errors were estimated in a similar fashion as for PACS by measuring the flux in randomly placed apertures on empty parts of the background and determining the variations between these background flux measurements. All objects in this paper with Spitzer data are detected at high significance in the five bands. The resulting photometry is summarized in Table 2 and is usually consistent with measurements published previously, where available (e.g., Jiang et al. 2006, 2010; Hines et al. 2006). The 24 \(\mu m\) images are presented alongside the PACS and SPIRE 250 \(\mu m\) images in Figure 1.

Our multi-wavelength data set, and in particular the Spitzer 24 \(\mu m\) images, provide a tool for determining the exact position of the quasar in the Herschel bands. Since we can often identify several sources per field that are visible both at Spitzer and at Herschel wavelengths, the exact location of the quasar in the FIR maps can be determined from the relative positional information. With this procedure we can robustly identify faint Herschel detections with the quasars as well as avoid misidentifications due to nearby objects. During this exercise we observe absolute spatial offsets between Spitzer and Herschel of
## Table 2

Infrared Photometry

| Name                | $F_{3.6\mu m}$ | $F_{4.5\mu m}$ | $F_{5.8\mu m}$ | $F_{8.0\mu m}$ | $F_{12\mu m}$ | $F_{24\mu m}$ | $F_{100\mu m}$ (mJy) | $F_{160\mu m}$ (mJy) | $F_{250\mu m}$ (mJy) | $F_{500\mu m}$ (mJy) |
|---------------------|----------------|----------------|----------------|----------------|---------------|---------------|-----------------------|-----------------------|-----------------------|-----------------------|
| J0203+0012          | 80 ± 1         | 88 ± 1         | 106 ± 6       | 106 ± 7       | 353 ± 111     | 680 ± 44      | <3.3                  | <5.4                  | <15.6                 | <13.5                 | <18.0                 |
| J0338+0021          | 81 ± 2         | 71 ± 2         | 82 ± 7        | 158 ± 9       | <355          | 1187 ± 52     | 10.7 ± 1.0            | 18.5 ± 2.0            | 19.6 ± 5.9             | 18.5 ± 6.2             | 12.6 ± 6.5             |
| J0756+4104          | 61 ± 2         | 62 ± 2         | 70 ± 6        | 123 ± 7       | <732          | 698 ± 36      | 6.2 ± 0.8              | 9.0 ± 1.0              | 11.4 ± 5.3             | 19.0 ± 4.8             | 19.9 ± 5.0             |
| J0818+1722          | 168 ± 2        | 200 ± 2        | 167 ± 8       | 216 ± 10      | 425 ± 127     | 1004 ± 30     | <3.0                  | <5.1                  | <14.7                 | <13.8                 | <15.3                 |
| J0840+5624          | 58 ± 1         | 80 ± 1         | 61 ± 7        | 62 ± 6        | ...           | 440 ± 29      | <2.7                  | <4.2                  | <15.3                 | <13.5                 | <15.3                 |
| J0927+2001          | 47 ± 2         | 50 ± 2         | 42 ± 7        | 76 ± 7        | <757          | 639 ± 40      | <3.0                  | <3.9                  | 13.1 ± 5.3             | 15.3 ± 5.0             | 19.5 ± 5.8             |
| J1044+0012          | 106 ± 2        | 131 ± 2        | 108 ± 8       | 186 ± 9       | <398          | 1436 ± 39     | 6.7 ± 0.8              | 8.5 ± 1.0              | <15.3                 | <12.6                 | <16.5                 |
| J1048+4637          | 110 ± 2        | 120 ± 2        | 95 ± 7        | 128 ± 7       | <315          | 818 ± 41      | <2.1                  | <3.0                  | <14.4                 | <14.1                 | <18.6                 |
| J1148+5251          | 137 ± 3        | 146 ± 2        | 143 ± 8       | 214 ± 8       | 304 ± 100     | 1349 ± 39     | 3.9 ± 0.6              | 7.4 ± 1.7              | 21.0 ± 5.3             | 21.8 ± 4.9             | 12.4 ± 5.7             |
| J1335+3533          | 66 ± 1         | 69 ± 1         | 55 ± 4        | 57 ± 6        | <311          | 483 ± 32      | <2.7                  | <3.0                  | <13.5                 | <14.1                 | <18.6                 |
| J2054+0005          | <18            | <48            | ...           | ...           | <162          | <1932         | <2.7                  | 9.8 ± 1.3              | 15.2 ± 5.4             | 12.0 ± 4.9             | <19.5                 |

Notes. Upper limits correspond to 3σ. Photometry in Columns 2–5 and 7 is from *Spitzer* observations, except for J2054+0005. Column 6 is based on data from the WISE All-Sky Survey. Columns 8–12 refer to *Herschel* data.

1. The *Spitzer* values of this source may include some contamination from a nearby galaxy (see text). The WISE observations do not separate the objects and the quoted catalog flux has to be taken with caution.
2. No 12 μm photometry could be performed due to severe blending with a bright nearby source.
3. This is the only source also observed at 70 μm where we measure a flux of 2.9 ± 0.6 mJy.
4. This object was not observed with *Spitzer*. Data in Columns 2, 3, and 7 are based on aperture photometry on WISE All-Sky Survey atlas images at 3.4, 4.6, and 22 μm, respectively.
typically $\lesssim 2^\circ$, in line with expectations from the absolute pointing accuracies.

### 2.4. WISE

The all-sky data release of the Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010) was queried for photometry or upper limits in the 12 $\mu$m band which can fill the gap in the Spitzer photometry between 8 and 24 $\mu$m. Only three quasars in this paper are detected at 12 $\mu$m and their significance is low ($\lesssim 3.5\sigma$, Table 2). Some objects (e.g., J2054−0005) are not detected in any WISE band, and consequently no upper limits are available in the point-source catalog. For such sources we performed aperture photometry on the WISE atlas images to determine upper limits, following the guidelines in the explanatory supplements to the WISE All-Sky Data Release Products (Cutri et al. 2012).

### 2.5. Supplemental Data

Additional data from the literature were compiled, mainly in the observed NIR or millimeter regimes and often taken from the discovery papers. The latest data release of the UKIDSS survey (Lawrence et al. 2007) was also checked which yielded additional photometry in the NIR for six objects.

### 3. ANALYSIS

#### 3.1. SED Components

In combination with other supplemental data from the literature (Section 2), we compile SEDs covering a rest frame wavelength range of typically 0.1–400 $\mu$m (see Figures 2 and 3). These SEDs are then fitted with a combination of models to represent the different components contributing to the observed SED. For this purpose we have divided our sample into two groups, depending on the amount of data available to constrain the fitted components. Objects detected in at least two Herschel bands were subject to full SED fits (five sources), except J2054−0005, for which the lack of strong photometric constraints at rest frame wavelengths $<10$ $\mu$m (no Spitzer observations and only WISE upper limits) prevented a full SED fit. In our fits we consider four distinct components.

1. A power law in the UV/optical regime which represents the emission from the accretion disk. We extend this component into the NIR and introduce a break to the Rayleigh–Jeans slope of $F_\nu \propto \nu^\beta$ at 3 $\mu$m in the rest frame (Hönig & Kishimoto 2010). In the fitting, the power-law slope in the UV/optical and the overall normalization are free parameters.

2. A blackbody of typically 1300 K temperature, thus peaking in the rest frame NIR. Empirically, such a component is often required to fit the optical through MIR SEDs of luminous quasars (e.g., Barvainis 1987; Gallagher et al. 2007; Mor et al. 2009; Leipski et al. 2010a) and is generally interpreted as a signature of hot (graphite) dust close to the sublimation temperature.

3. A clumpy torus model from the library of Hönig & Kishimoto (2010) to account for the active galactic nucleus (AGN) heated dust from the “dusty torus” in the central parts of the AGN. This component dominates the MIR and is important to disentangle, to first order, the contributions from the nuclear dust to the rest frame FIR emission. Besides the choice of a particular model (see below), the absolute scaling of the model is the only free parameter for this component.

4. A modified blackbody to account for possible FIR excess emission (over the AGN heated torus) which we here interpret as powered by star formation. For this component we fix the emissivity index $\beta$ to a value of 1.6 (e.g., Beelen et al. 2006; Wang et al. 2008a; but see Section 4.3). The temperature of the modified blackbody and the normalization are free parameters.

#### 3.2. Fitting Procedure

The torus models we consider here are available for seven different inclinations (starting at 0° and increasing in steps of 15°). For each inclination, Hönig & Kishimoto (2010) provide models of various combinations of parameters (opening angle, radial dust distribution, etc.). Our fitting procedure takes one of the torus models and fits a linear combination of the four components to the observed SED via chi-square minimization using MPFIT (Markwardt 2009) in IDL. We then cycle through all torus models in the library and repeat the fitting for each of them. However, for efficiency we limit the torus component to models with inclinations $\leq 45^\circ$, which seems reasonable given that we observe luminous and largely unreddened type-1 quasars. This leaves a total of 959 different torus models. We visually inspect the best-fitting 10% of the model combinations to confirm the fits.

With this approach we do not intend to develop a highly accurate model for the full SED emission in these objects. For the current work we aim to construct a physically motivated approximation that yields a reasonable description of the observed SEDs which allows us to isolate excess FIR emission and to account for (to first order) contributions of the AGN heated nuclear dust to the FIR photometry.

As outlined above, our fitting includes an additional, empirically motivated 1300 K blackbody in the NIR. We have also performed the fits excluding this component, only fitting a power-law, a torus model and a FIR modified blackbody. The comparison between the two cases shows that the fits including the NIR blackbody generally represent the observed photometry better. This is particularly apparent in wavelength regions dominated by very hot dust ($\lambda_{\text{rest}} \sim 1–3$ $\mu$m), in the overlap region between the torus and the FIR blackbody ($\lambda_{\text{rest}} \sim 20–30$ $\mu$m) and in the fit at $\lambda_{\text{rest}} \gtrsim 100$ $\mu$m. The temperatures of the FIR dust component also come out consistently lower (by about 5–10 K) in fits including the additional NIR blackbody.

Recall that the additional NIR component contributes significantly (or dominantly) to the short infrared wavelengths. In cases where this component is absent, torus models with a strong emphasis on emission at $\lambda \lesssim 10$ $\mu$m are favored in the fits to accommodate (in particular) the MIPS photometry. By design such torus models contribute less flux at longer wavelengths ($\lambda \gtrsim 20$ $\mu$m), thus requiring a hotter FIR component to match the Herschel photometry. This in turn negatively affects the fit in the observed submillimeter/millimeter regime. Including the NIR component, more power in the torus component can shift to slightly longer wavelengths, allowing a cooler FIR component and providing a better overall fit to the data. The need to add an additional hot component to torus models when fitting type-1 AGN SEDs has also been noted by e.g., Mor & Netzer (2012). NIR reverberation mapping observations (e.g., Suganuma et al. 2006) show that the size of the emitting region of this very hot dust is a factor of $\sim 20$ smaller than the torus as measured in the MIR via interferometry (L. Burtscher et al., in preparation).
Figure 2. Observed SEDs of millimeter-detected quasars with at least two Herschel detections; for these objects multi-component SED fits were carried out as outlined in Section 2. The SED fit is performed using a power-law in the UV/optical (dotted line), a 1300 K blackbody in the NIR (dot-dashed line), a torus model in the NIR/MIR (short dashed line), and a modified blackbody in the FIR with emissivity index $\beta$ fixed to 1.6 (long dashed line). The blue solid line corresponds to the sum of the fitted components which here represent the overall best fit. Thus, the temperature of the FIR component here may differ slightly from the overall mean temperature determined from all acceptable fits as presented in Table 3. The squares correspond to the new Herschel data.

(A color version of this figure is available in the online journal.)
Figure 3. Observed SEDs of millimeter-detected quasars without *Herschel* detections. Despite SPIRE detections, the object J2054−0005 is included here because the poor constraints on the rest frame optical through MIR SED prevent detailed SED fits.
supporting this additional complexity in the distribution of the AGN-heated dust. The following results and discussion will therefore be based on the fits including the additional NIR blackbody.

4. RESULTS

4.1. Detection Rates

In our new Herschel observations we detect six out of eleven sources (Table 2). Typically, the quasars are either detected in all five bands or not at all with Herschel. The exceptions are J0927+2001 which is detected with SPIRE but not with PACS and J1044−1025 for which the opposite is the case.

From the 10 objects observed with Spitzer, all are detected in all bands. With WISE at 12 μm only three objects are detected and at low significance. More detailed information on the individual objects can be found in the Appendix.

4.2. The Temperature of the FIR Dust

Previous studies of star formation in high-redshift (z > 5) quasars often had to rely on single band millimeter emission as a tracer for the starburst heated dust (e.g., Bertoldi et al. 2003; Wang et al. 2008a). FIR luminosities were determined by fitting a single modified blackbody to the millimeter photometry and integrating under this component. Since no knowledge about the temperature of the dust was at hand for most cases, typical values found for FIR bright quasars at lower redshift (z ~ 2–4) were assumed (e.g., T = 47 K, β = 1.6; Beelen et al. 2006). This approach has been tentatively supported for some high-redshift quasars by ground-based observations at 350 μm (Wang et al. 2008b, 2010).

The new multi-wavelength FIR photometry now allows us to estimate the temperature of the FIR emitting dust directly while simultaneously accounting for the contributions from AGN heated nuclear dust to the infrared. In Figure 2 we present the SEDs of the five objects which are detected in at least two Herschel bands and their accompanying best fits.

As explained above, details of the SED of the AGN heated dust torus affects the shape (and temperature) of the FIR component. We have taken this into account when calculating the uncertainties of the dust temperature (see Section 4.5). The values of T_{FIR} we obtain here for these five objects are reported in Table 3. We clearly see a range of temperatures among these objects, spanning almost 20 K.

Figure 4. Relative contributions of the NIR bump plus torus emission (presumably AGN-powered; blue) and the FIR blackbody (presumably star-formation powered; red) to the total SED fit as a function of wavelength. The vertical gray line indicates the wavelength range sampled by the observed 350 μm band for the redshifts of the sources in this plot (z = 5.0–6.4).

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

One important result from the SED fits in Figure 2 is that the flux at λ_{rest} ≥ 50 μm is usually dominated by the FIR excess emission with only minor contributions from the AGN heated torus. This is further illustrated in Figure 4 where we show the fractional contribution of the hot dust plus dusty torus component (both presumably powered by the AGN) compared with the contributions from the FIR excess component, which may be powered by star formation. As indicated in this figure, the SPIRE 350 μm band is typically dominated by emission from the FIR blackbody for the redshifts considered here. In fact, fitting only a single modified blackbody (β = 1.6) to the photometry at λ ≥ 350 μm gives very similar dust temperatures compared to the full SED fits.

This result can immediately be utilized for an estimate on the dust temperature for objects which do not qualify for full SED fits (see Figure 3). In these cases we use the 250 GHz detection as an anchor for the (modified) blackbody while the FIR upper limits at λ ≥ 350 μm (mostly from SPIRE) allow us to constrain the maximum permitted temperature of this component. Because of our findings from the full SED fits (Figure 4) we can assume that our upper limits to the dust temperature are reasonably robust when limiting the fits to λ ≥ 350 μm, even without suitable constraints on the AGN dust emission in these objects. We determine dust temperatures of ≤ 57 K, with J0818+1722 being the only exception (T_{FIR} < 71 K). However, the latter value has to be taken with caution because the 250 GHz photometry of this source could be contaminated by the emission from the nearby galaxy that is detected in most infrared bands (see notes on individual objects in the Appendix and Figure 1).

4.3. The Emissivity Index β

In the previous fits, the emissivity index β was fixed to a value of 1.6 to enable the comparison with earlier literature studies. The good photometric coverage in the FIR and submillimeter for some of our objects now allows us to explore how far β can be constrained using the quasar SEDs. For such a study, additional photometry at lower frequencies (typically around 90 GHz in the observed frame) is very important as it helps to further constrain the Rayleigh–Jeans tail of the fitted dust component. In fact, considering only photometry at ν_{obs} > 250 GHz does not provide good constraints on β (or the FIR dust temperature) if both parameters are kept free during fitting. Photometry at ~90 GHz in combination with Herschel FIR detections is available for four objects in our sample. Re-fitting the SEDs as outlined previously but now keeping β as a free parameter, we find relatively high β values (2.0–2.7) combined with relatively low temperatures (~33 K, but still 54 K for J1148+5251). The integrated luminosity of the FIR dust when determined from these new fits remains virtually unchanged as compared to a fixed β approach. We caution, however, that a reliable measure of β is hard to obtain in these objects because the peak of the dust emission is not well defined (or isolated) in the SED due to the strong nuclear dust emission from the torus. Therefore, the peak wavelength (and temperature) of the FIR blackbody depends on the choice of the torus model, which adds additional uncertainty in the determination of β.
is the dust absorption coefficient at 250 μm (i.e., the modified blackbody) between 8 and 1000 μm as determined from the residuals between the global fit and the observed data in the models of Draine (2003), and also derive an estimate for the dust masses in the star forming regions:

\[ M_{\text{dust}} = \frac{S_{250 \mu m} D_L^2}{\kappa_{250 \mu m} B_\nu(250 \mu m, T_{\text{FIR}})}, \]

where \( S_{250 \mu m} \) is flux level at a rest frame wavelength of 250 μm as determined from the fit, \( D_L \) is the luminosity distance, \( \kappa_{250 \mu m} \) is the dust absorption coefficient at 250 μm as determined from the models of Draine (2003), and \( B_\nu(250 \mu m, T_{\text{FIR}}) \) is the value of the Planck function with temperature \( T_{\text{FIR}} \) at a wavelength of 250 μm. The results are also reported in Table 3.

### 4.5. Error Estimates on Physical Parameters

In order to estimate uncertainties in the derived parameters we studied the distribution of their values resulting from all the fitted models (\( N \sim 1000 \); as outlined in Section 3.2 we only include torus models with inclinations of \( \leq 45^\circ \)). This also allows us to account for the influence the choice of a particular torus model has on these parameters.

As a first step, we calculated for all the fitted models the residuals between the global fit and the observed data in the infrared (\( \lambda_{\text{rest}} > 1 \mu m \)) and determined the error-weighted rms for these points. A typical distribution of the resulting rms values is presented in panel “(a)” of Figure 5 (we here use the quasar J0756+4104 as an example to demonstrate our approach). In this figure we see a clear peak at low rms values representing a family of good fits, with an extended tail to large rms values corresponding to increasingly worse model representations of the observed SED. We then fitted the right side of the rms peak with a Gaussian (dashed line). All fits with an rms value within 3σ of the centroid value of the Gaussian are identified as acceptable model fits. The values corresponding to these fits are marked as blue and hashed regions in all panels of Figure 5 and are used for estimating uncertainties on the derived values.

Each of the \( N \sim 1000 \) model fits provides a value for the temperature of the modified blackbody in the FIR \( (T_{\text{FIR}}, \text{ panel “(b)” in Figure 5}) \). From the temperature and the normalization of this component we can then calculate (see Section 4.4) \( L_{\text{FIR}} \) (panel “(c)”\)), a star-formation rate (panel “(d)”\)), and a dust mass \( M_{\text{dust}} \) (panel “(e)”). In each histogram we fit the parameter values obtained from the acceptable fits (as determined from the residual rms distribution; blue and hashed regions) with a Gaussian (dashed line). This Gaussian fit provides us with a mean parameter value (centroid) and an uncertainty (σ) for each fitted object. These results are reported in Table 3.

### 5. DISCUSSION

#### 5.1. Comparison with Previous Studies

The average temperature of the modified blackbody used to model the FIR emission is comparable to the \( \sim 47 \) K measured for lower redshift FIR bright quasars (Beelen et al. 2006). This finding is confirmed by the average SEDs presented in Section 5.2 below.

While this is true on average, we see a significant spread in dust temperature (\( \sim 20 \) K) between individual objects, even for comparable FIR luminosities. Despite the low number of objects

| Name     | α_{UV/mm} | L_{250 mm}/μm | L_{NIR/MIR}/μm | T_{FIR} (K) | L_{FIR} (10^{13} L_\odot) | % of L_{FIR} | SFR (10^3 M_\odot yr^{-1}) | M_{FIR} (10^8 M_\odot) |
|----------|------------|---------------|----------------|-------------|------------------------|-------------|-----------------------------|---------------------|
| J0203+0012 | −0.16 ± 0.02 | 9.6 ± 0.2     | <10.5          | 57 ± 1.3    | ...                    | <2.2        | ...                         | ...                 |
| J0338+0021 | −0.39 ± 0.03 | 4.8 ± 0.3     | 18.1 ± 0.9     | 47 ± 1.1    | ...                    | 24          | 1.8 ± 0.6                   | 6.8 ± 2.0            |
| J0756+4104 | −0.42 ± 0.03 | 4.1 ± 0.3     | 10.3 ± 0.3     | 40 ± 1.1    | ...                    | 35          | 19.0 ± 0.3                  | 15.9 ± 1.6           |
| J0818+1722 | −0.68 ± 0.02 | 12.5 ± 0.2    | <8.3           | 71 ± 1.8    | ...                    | 3.1         | ...                         | ...                 |
| J0840+5624 | −0.31 ± 0.02 | 6.1 ± 0.2     | <8.8           | 45 ± 0.9    | ...                    | 1.6         | ...                         | ...                 |
| J0927+2001 | 0.00 ± 0.03  | 5.5 ± 0.2     | <7.3           | 50 ± 1.3    | 62                     | 2.1 ± 0.3   | 5.3 ± 0.4                   | ...                 |
| J1044−0125 | −0.33 ± 0.03 | 9.9 ± 0.3     | 19.3 ± 0.5     | <53         | 1.2                    | <2.1        | ...                         | ...                 |
| J1048+4637 | −0.33 ± 0.02 | 12.4 ± 0.2    | <11.5          | 56 ± 1.6    | 2.7 ± 0.3              | 54          | 4.6 ± 0.5                   | 4.7 ± 0.6            |
| J1148+5251 | −0.35 ± 0.03 | 15.3 ± 0.2    | 16.6 ± 0.9     | 59 ± 3      | 54                     | 0.8         | ...                         | ...                 |
| J1335+3533 | −0.33 ± 0.02 | 6.3 ± 0.2     | <7.3           | 55 ± 1.4    | ...                    | 2.4         | ...                         | ...                 |
| J2054−0005 | −0.22 ± 0.02 | 3.0 ± 0.2     | <22.5          | 54 ± 1.3    | <2.2                   | ...         | ...                         | ...                 |

**Notes.** Columns: (2) Power-law slope in the UV/optical \( (F_\nu \sim \nu^{\alpha}) \); (3) integrated luminosity between 0.1 and 1 μm of the power-law component; (4) integrated luminosity between 1 and 1000 μm of (presumably) AGN powered dust emission (NIR blackbody and torus component combined); (5) temperature of the modified blackbody fitted in the FIR; (6) integrated luminosity between 8 and 1000 μm of the star-formation powered FIR component; (7) percentage contribution of star formation to total FIR luminosity between 8 and 1000 μm; (8) star-formation rate derived from \( L_{\text{FIR}} \) using Kennicutt (1998); (9) dust mass derived from the star-formation powered FIR component following Equation (1).

a We here assume that the measured 250 GHz flux comes from the quasar, but it might actually be contaminated by a nearby galaxy, leading to erroneous results. See the Appendix for details on this object.

b For J1044−0125 the detections in both PACS bands allowed us to constrain the torus component (and thus to perform a full SED fit), but due to the SPIRE upper limits we can only provide upper limits for the values derived from the FIR blackbody.
for which such fits can be performed, this finding highlights that the choice of the dust temperature can add uncertainty to the estimate of $L_{\text{FIR}}$ and $M_{\text{dust}}$, in particular for objects with only single photometric measurements and thus no individual constraints on $T_{\text{FIR}}$.

A related issue is that of possible AGN contributions to the heating of the FIR dust which will be discussed briefly in the following section.

We also find that in our modeling strategy the FIR component can be isolated from the torus component if only data at $\lambda_{\text{rest}} \gtrsim 50 \mu m$ are considered (see Section 4.2 and Figure 4). Consequently, single-component fits to data at these wavelengths yield estimates of the FIR luminosity, temperature and dust mass that match the values based on the full SED fits. This result validates the approach in previous studies of high-$z$ quasars (Bertoldi et al. 2003; Beelen et al. 2006; Wang et al. 2008a, 2008b) in which single-component fits to (ground-based) photometry at $\lambda_{\text{obs}} \gtrsim 350 \mu m$ were used to derive physical parameters (with the caveat of unknown dust temperature in some of these studies). It also adds further significance to the upper limits on $T_{\text{FIR}}$, $L_{\text{FIR}}$, and SFR we determine for the remainder of our sample where we are limited to single-component fits at $\lambda_{\text{obs}} \gtrsim 350 \mu m$.

The strong overlap between the torus and the FIR components in our fits does not provide good constraints on the emissivity index $\beta$ of the latter component. The difficulty of determining reliable $\beta$ estimates in objects with a strong AGN is also apparent from the literature: Priddey & McMahon (2001) find a high $\beta$ value of $\sim 2$ (with a FIR dust temperature of 41 K) by combining the available photometry for a number of $z \sim 4$ quasars into a single SED and using this global SED to constrain a modified blackbody fit. On the other hand, using a similar approach (and much of the same data), Beelen et al. (2006) find $\beta \sim 1.6$ and $T_{\text{FIR}} \sim 47$ K for a sample of quasars with $z = 1.8$–6.4.

5.2. Stacking of the FIR Data

In order to better constrain the FIR emission of the SPIRE non-detected objects, we stacked the individual SPIRE observations at the nominal position of the quasar (excluding J0818+1722 due to possible confusion issues).9 Even in the stacked images no significant detection was achieved (see Figure 6). Stacking the corresponding PACS data we recover a faint ($\sim 3\sigma$) average signal at 100 and 160 $\mu m$. We iterated during the stacking, leaving a different source out of the stack for every iteration to verify that the result is not biased by any individual object. Differences between these stacks were usually smaller than the uncertainty on the photometry of the total stack. The photometry was performed in an identical manner to the individual frames and as outlined in Section 2.

Using the stacked Herschel fluxes and combining them with stacked WISE data as well as averaged Spitzer and millimeter photometry, we can produce an average SED for the FIR non-detected objects which is presented in Figure 7. Performing the same stacking/averaging procedure for the objects detected in the FIR individually (excluding J1148+5251 due to possible confusion issues) also provides us with an average SED for these objects.

Fitting the average FIR SEDs with a modified blackbody (at $\lambda_{\text{obs}} \gtrsim 350 \mu m$, $\beta = 1.6$) reveals dust temperatures of 47 K for the stack of the individually detected objects, as expected considering the individual FIR dust temperatures of the objects in this stack (Table 3). For the average SED of the objects individually undetected in SPIRE we determine an upper limit of 49 K which is lower than the upper limits determined individually (Table 3). These temperatures are very similar to the values commonly adopted for millimeter detected quasars

9 We also excluded J1044−0125 from this stack. While the source is also not detected with SPIRE, its PACS detection would influence the average PACS flux of this subsample significantly.
In contrast, for a similar scaled UV/optical emission, the average infrared SED of the SPIRE detected quasars (red points in Figure 7) exceeds the scaled template significantly at any wavelength $\lambda_{\text{rest}} \gtrsim 1 \mu m$. This includes the presumably AGN powered dust emission at short infrared wavelengths ($\lambda_{\text{rest}} \lesssim 20 \mu m$) as well as the FIR emission possibly powered by additional star formation.

The observed discrepancy between the average SEDs in Figure 7 is somewhat puzzling. Both groups of objects have similar UV/optical properties (on average), indicating that their black holes grow at comparable rates. Now, assuming that the NIR and MIR emission is powered by the AGN, the objects with individual Herschel detections (red symbols) convert a higher fraction of their accretion luminosity into reprocessed dust emission. This could, in principle, be caused by a different dust geometry (or dust content) in the inner parts of these objects. This in turn could also lead to increased contributions of AGN powered dust emission at FIR wavelengths. If AGN-powered dust emission extends further into the FIR than anticipated by the torus models we utilize here, the values for the inferred star-formation luminosity (and star formation rates) in these objects (Table 3) would be overestimated.

While a detailed discussion of this issue is beyond the scope of this paper, it is worth keeping in mind that the AGN may be contributing to the heating of the FIR dust depending on the dust distribution and geometry.

6. SUMMARY AND CONCLUSIONS

New Herschel observations of 11 $z > 5$ quasars with detections at 1.2 mm are combined with data at other wavelengths to analyze their full SEDs covering the rest frame wavelength range of $\sim 0.1–400 \mu m$. Our results can be summarized as follows.

1. Six out of the eleven objects are detected in at least two of the five Herschel bands. Five of them have sufficient data coverage and quality to allow full SED fits.

2. In all cases where such fits could be performed, AGN powered emission from a dusty torus is not sufficient to explain the observed FIR fluxes. An additional FIR...
component is required to model the SEDs. Similar to other studies of luminous (but lower redshift) quasars, we note the need for a hot (~1300 K) dust component to account for the strong rest frame NIR emission.

3. The additional FIR component was modeled as a modified blackbody and shows temperatures of $T \sim 40-60$ K. We interpret this emission as being powered by star formation with luminosities of $L_{\text{FIR}} \sim 10^{13} L_\odot$ which translate into star-formation rates of several thousand solar masses per year.

4. Our fits also allow us to estimate that the contributions of the AGN powered dust to the infrared SED are small at wavelengths $\lambda_{\text{rest}} \gtrsim 50 \mu m$. For the redshifts of our objects this implies that the star-formation powered FIR component can be isolated and characterized adequately by single-component fits if only photometric measurements at $\lambda_{\text{obs}} \gtrsim 350 \mu m$ are considered. This explains the good match for the temperature and luminosity of the FIR emission with previous studies of such objects which relied on (ground-based) observations at $\lambda_{\text{obs}} \gtrsim 350 \mu m$.

5. By stacking the Herschel data of individually undetected sources we recover a signal in PACS but not in SPIRE. We use this stacking approach to construct average SEDs for objects with and without individual Herschel detections. We find that the high-redshift objects which are individually undetected with Herschel show an SED similar to quasar templates constructed from lower redshift and lower luminosity objects.

6. The average SED of the Herschel detected objects, on the other hand, shows a surplus of NIR and MIR emission relative to the UV/optical when compared to the Herschel nondetections or to quasar templates. This may suggest a correlation between strong FIR emission (here modeled as star-formation powered) and strong MIR emission (here modeled as AGN powered), and possibly indicates significant AGN contributions to the FIR emission.

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Facilities: Herschel, Spitzer

APPENDIX

Comments on Individual Objects

Object names are given in the format Jhhmm+ddmm. For full, NED compatible object designations see Table 1.

J0203+0012 ($z = 5.72$). The combined optical and NIR spectroscopy by Mortlock et al. (2009) reveals broad absorption line features in this quasar which could be one explanation for the abrupt change in SED slope observed at $\lambda_{\text{rest}} \lesssim 0.3 \mu m$ (Figure 3). It is fairly radio bright at 1.4 GHz compared to most $z \sim 6$ quasars (Wang et al. 2008) and is detected at 250 GHz with a flux of 1.85 ± 0.46 mJy (Wang et al. 2011).

These authors did not detect the quasar in CO(6–5) nor in the corresponding continuum. While clearly seen in all our Spitzer observations, no detection was achieved with Herschel. Several nearby galaxies can be identified in SDSS and IRAC, some of which are prominent in most infrared channels. The closest bright object is ~30′ northeast of the quasar. From SDSS spectroscopy of some galaxies in this area it appears that they might belong to a foreground cluster at redshift of $z \sim 0.077$.

J0338+0021 ($z = 5.03$). This source was detected at 250 GHz (3.7 ± 0.3 mJy), but remained undetected at 1.4 GHz (Carilli et al. 2001). The 850 μm flux is measured to be 11.9 ± 2.0 mJy (Priddey et al. 2003). Matolino et al. (2007) report CO(5–4) emission from the quasar, but no continuum at 95.6 GHz is detected. Inspection of the field at optical through FIR wavelengths reveals a nearby source ~15″ to the west of the quasar. This object is clearly visible in the SDSS r and i bands, as well as with IRAC and MIPS. In all these filters, the quasar is typically the brighter source, a situation which reverses at 100 and 160 μm where the nearby object is ~1.4 and ~1.3 times brighter, respectively, than the quasar. In all SPIRE bands, however, we only detect a single source. Interestingly, the quasar and the nearby object can both be seen in ground-based 350 μm observations (Wang et al. 2008b) and the flux of the quasar (17.7 ± 4.4 mJy beam^−1) is very comparable to the SPIRE 350 μm flux determined for the single detection (18.5 ± 6.0 mJy). This suggests that the SED of the source close to the QSO peaks somewhere around the PACS bands but does not contribute significantly at wavelengths >350 μm.

J0756+4104 ($z = 5.11$). The 250 GHz flux (5.5 ± 0.5 mJy) has been presented by Petric et al. (2003) who also detect the source at 1.4 GHz and constrain the size of the radio emission to <2″.3. Priddey et al. (2008) report detections at 850 μm (11.2 ± 1.0 mJy) and 450 μm (16 ± 5 mJy) where “the source clearly appears elongated” in the 850 μm map at a position angle of ~70″. We detect the quasar in all our five Herschel bands, but the significance is often marginal. Our flux at 350 μm is consistent with the ground-based measurements of Wang et al. (2008b).

J0818+1722 ($z = 6.00$). Radio continuum emission at 1.4 GHz is clearly detected (Wang et al. 2007) and the 250 GHz continuum is observed at the 3σ level (1.19 ± 0.38 mJy; Wang et al. 2008a). Close inspection of our multi-wavelength images reveals a resolved foreground galaxy ~6″ north-east of the quasar. Both objects, the galaxy and the quasar, are individually detected by MIPS at 24 μm and in shorter wavelength bands. However, only a single source is detected in PACS and SPIRE (note that the spatial resolution of Herschel/PACS at 100 μm is comparable to Spitzer/MIPS at 24 μm). From the relative positions of other sources in the field we can identify the detection at 100, 160, and possibly at 250 μm with the foreground galaxy. It is conceivable that the faint (3σ) detection at 350 μm is also due to this source. No detection is achieved at 500 μm. In the light of these results, higher resolution millimeter observation are clearly needed to determine the source of the 250 GHz continuum emission.

J0840+5624 ($z = 5.84$). We do not detect this source in our PACS nor in the SPIRE data. The quasar has been detected at 250 GHz (3.20 ± 0.64 mJy), but not at 1.4 GHz (Wang et al. 2007). CO emission is seen in this source (but no continuum at either 85 GHz or 101 GHz) and the 350 μm emission is “marginally detected” from the ground (Wang et al. 2010), which is consistent with our SPIRE 350 μm upper limit. Wang et al. (2010) also report the presence of another source visible
at 350 μm as well as at 1.4 GHz located ~30′′ north-west of the quasar. This source is also detected in all our infrared bands. Inspection of the IRAC maps reveals this detection to coincide with two close objects which could be two slightly resolved galaxies separated by ~1′′ as seen on an archival HST/WFC3 image in the F105W filter.

\[ J0927+2001 \] (\( z = 5.77 \)). Previously detected at 250 GHz (4.98 ± 0.75 mJy; Wang et al. 2007) as well as in CO and in the 90 GHz continuum (Carilli et al. 2007). The 350 μm observations by Wang et al. (2008b) show the quasar (17.7 ± 5.7 mJy beam\(^{-1}\)) and a secondary source of equal brightness 15′′ to the southeast. While the quasar detection was confirmed in Wang et al. (2010) with better sensitivity (11.7 ± 2.4 mJy beam\(^{-1}\)), the secondary source was not. We detect the quasar with SPIRE, but not with PACS.

\[ J1044−0125 \] (\( z = 5.78 \)). This well studied quasar shows a broad CIV absorption feature in its spectrum (e.g., Maiolino et al. 2001; Goodrich et al. 2001). The continuum emission is detected at 850 μm (5.6 ± 1.0 mJy; Priddey et al. 2008) and at 250 GHz (1.82 ± 0.43 mJy; Wang et al. 2008a). Wang et al. (2010) report the detection of CO(6–5) but can only give an upper limit on the continuum at 102 GHz. The quasar is not seen in ground-based observations at 350 μm (Wang et al. 2010) and 1.4 GHz (Petric et al. 2003). We detect the quasar with PACS, but not with SPIRE.

\[ J1048+4637 \] (\( z = 6.23 \)). While clearly detected in the available Spitzer bands, this quasar remains undetected in our Herschel photometry. Wang et al. (2008b) only give an upper limit on the 350 μm flux, just like Robson et al. (2004) at 450 and 850 μm. These authors, however, note that based on the published 1.2 mm detection (3.0 ± 0.4 mJy; Bertoldi et al. 2003), the SCUBA 850 μm observations are deep enough to enable the detection of the source with 4σ significance given a dust temperature of 40 K.

\[ J1148+5251 \] (\( z = 6.42 \)). This famous object was the highest redshift quasar known for half a decade (Fan et al. 2003; Wilott et al. 2007) and as such has been studied at many wavelengths, including the millimeter and submillimeter regime. We also have observed this quasar previously with Herschel/PACS and reported detections at 100 and 160 μm (Leipski et al. 2010b). Surprisingly, we discovered a secondary object ~10″ north-west of the quasar which is brighter at 160 μm but can still be identified at 100 μm. Ground-based data at 350 μm (Beelen et al. 2006) and 250 GHz (Bertoldi et al. 2003) revealed an intriguing elongation of the quasar detection in the direction of the second source. We argued in our previous paper that this could be an indication for the presence of the secondary source. A possible counterpart is also seen in the 24 μm images. In the IRAC band, three sources are detected around the position of this secondary source, two of which can also be identified on deep Hubble Space Telescope (HST) images with the Advanced Camera for Surveys camera in the F850LP filter. Recently, new deep HST images from WFC3 in the NIR revealed also the third source seen in IRAC. This object is clearly detected, but faint in F125W and gets significantly brighter in F160W. This is our best candidate for a counterpart of the secondary source seen at 24, 100, and 160 μm. Surprisingly, however, follow-up observations with the Plateau de Bure Interferometer at 1.2 mm at ~1″ resolution did not yield a detection and the 3σ upper limit we derive is 0.9 mJy.

Since our initial photometry (Leipski et al. 2010b) we have re-observed the quasar with Herschel and obtained new images at 70, 160, 250, 350, and 500 μm. While the quasar itself is faintly detected at 70 μm, there is no sign for a secondary source. The new 160 μm observations confirm our earlier findings that the flux appears to come from two sources. The source complex is also detected in all SPIRE bands, but the spatial resolution is too low to identify a possible double source. Combining the multi-wavelength photometry of the secondary source, we find that the SED is consistent with a star-forming galaxy at \( z ∼ 2 \) with ultraluminous infrared galaxy-like luminosity (\( L_{IR,\text{SU}} \sim 10^{10} L_\odot \)).

\[ J1335+3533 \] (\( z = 5.90 \)). The optical spectrum of this source is quite unusual as it shows a typical quasar continuum but virtually no Lyα emission (Fan et al. 2006). At longer wavelengths, the quasar is seen in the Spitzer bands, but not in our Herschel data. Wang et al. (2010) report the detection of the CO (6–5) transition and give upper limits on the continuum at 350 μm and 100 GHz. The 250 GHz (2.34 ± 0.50 mJy) and 1.4 GHz continuum was detected by Wang et al. (2007).

\[ J2054−0005 \] (\( z = 6.04 \)). This is the only source in our sample for which we do not have Spitzer observations. The SDSS imaging featured a sufficient number of sources that could also be identified on the PACS maps to determine the position of the quasar accurately. The QSO is detected at 250 GHz (2.38 ± 0.53 mJy), but not at 1.4 GHz (Wang et al. 2008a). CO observations revealed the (6–5) transition but no continuum at 98 GHz (Wang et al. 2010). We see the source at 160 μm with PACS, but can only give an upper limit on the 100 μm flux. A faint 3σ−4σ source is visible at 250 and 350 μm. At 500 μm we run into confusion issues with a source located ~30′′ north of the quasar’s nominal position, which can also be identified (separate from the quasar) in the other SPIRE bands and at 160 μm. Since our photometry indicates that the FIR peak of the quasar in \( F_\nu \) falls close to the 250 μm band, we do not expect significant flux in the 500 μm channel. In a NIR spectrum, Ryan-Weber et al. (2009) see a very strong Mg II absorber at \( z_{\text{abs}} = 2.598 \).

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