The dust emission of high-redshift quasars

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Abstract.
The detection of powerful near-infrared emission in high redshift (z > 5) quasars demonstrates that very hot dust is present close to the active nucleus also in the very early universe. A number of high-redshift objects even show significant excess emission in the rest frame NIR over more local AGN spectral energy distribution (SED) templates. In order to test if this is a result of the very high luminosities or redshifts, we construct mean SEDs from the latest SDSS quasar catalogue in combination with MIR data from the WISE preliminary data release for several redshift and luminosity bins. Comparing these mean SEDs with a large sample of z > 5 quasars we could not identify any significant trends of the NIR spectral slope with luminosity or redshift in the regime 2.5 < z ≲ 6 and 10^{45} < νL_{ν}(1350Å) ≲ 10^{47} erg/s. In addition to the NIR regime, our combined Herschel and Spitzer photometry provides full infrared SED coverage of the same sample of z > 5 quasars. These observations reveal strong FIR emission (L_{FIR} ≳ 10^{13} L_⊙) in seven objects, possibly indicating star-formation rates of several thousand solar masses per year. The FIR excess emission has unusually high temperatures (T ∼ 65 K) which is in contrast to the temperature typically expected from studies at lower redshift (T ∼ 45 K). These objects are currently being investigated in more detail.

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 ∼ 6 show evidence for copious amounts of dust (e.g. Bertoldi et al. 2003; Wang et al. 2008; Leipski et al. 2010). This indicates the rapid metal enrichment of the interstellar medium within the first billion years after the big bang. Assuming that the observed far-infrared (FIR) emission of these objects is powered by star-formation, the luminosities imply star formation rates of up to a few thousand solar masses per year, possibly indicating the rapid formation of early galactic bulges.

For a more comprehensive picture of the dust emission at high redshifts we are currently analyzing PACS (100+160 µm) and SPIRE (250+350+500 µm) photometry of 71 quasars at z > 5 that have been obtained as part of our Herschel key project "The Dusty Young Universe". Complementary Spitzer data at shorter wavelengths were secured by our group to enable the study of the full optical through infrared SED of a large sample of quasars in the early universe.

In the course of this project we have now identified a number of high-z (z > 5) quasars with considerable FIR emission. They are clearly detected in our PACS and SPIRE observations and were previously unknown to have large infrared luminosities (Fig. 1). In combination with our existing Spitzer photometry, the Herschel data allow us study the full SED of these objects in the rest frame wavelength range 0.5 − 80 µm, which – most importantly – also covers the FIR peak of the SED.

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Figure 1. SED for the $z = 6.42$ quasar SDSS J1148+5251 including new Herschel data as well as information from the literature. Left: The quasar SED was fitted by a linear combination of the SDSS quasar template (Richards et al. 2006) and a modified black body (representing dust emission from star formation). Despite a reasonable match in the rest frame UV/optical and in the FIR, there exist a clear discrepancy between $\sim 1 - 10 \mu m$.

2. The signatures of hot dust in the rest frame near infrared

Most powerful AGN are strong sources of infrared radiation. This emission originates from dust heated by the accretion disk to various temperatures depending on its distance from the nucleus and its spatial distribution. In such a configuration, the sublimation temperature of the dust ($\sim 1500$ K) sets the inner boundary of the dust distribution in AGN. The dust at these temperatures predominately re-emits the absorbed energy in the rest frame near infrared. Thus, the spectral energy distribution in this regime provides us with a tool to study the AGN dust only a few parsec out from the core.

Using Herschel data and archival information, we noticed that common AGN templates (like the SDSS quasar template, Richards et al. 2006) do not match the amounts of hot dust emission between $\sim 1 - 10 \mu m$ in the UV/optical through sub-mm SED of the $z = 6.42$ quasar SDSS J1148+5251 (Leipski et al. 2010; Fig. 1). Interestingly, in the wavelength range where the discrepancy is most apparent ($\sim 1 - 5 \mu m$), the SED is particularly sensitive to the radial distribution of the innermost dust (however, this is not the only parameter that can influence the shape of the SED in this region; see Schartmann et al. 2008, Hönig & Kishimoto 2010).

The observed mismatch might be due to SDSS J1148+5251 being exceptional with a very high redshift ($z = 6.42$) and having extreme luminosity ($L_{\text{bol}} \sim 10^{47}$ erg/s). It is conceivable to assume that the dust distribution might be sensitive to the total luminosity of the heating source (i.e. the accretion disk) or even the evolutionary state of the system (i.e. high-$z$ vs. low-$z$).

The SDSS template is largely dominated by quasars around a redshift of $z \sim 2$. Only few objects at $z > 3$ are included. Furthermore, while all objects have SDSS and Spitzer IRAC data available, many objects lack NIR photometry (which was in these cases determined from scaling the Elvis et al. (1994) quasar template to the nearest observed data point). However, for a robust comparison with our $z > 5$ quasar SEDs – in particular with an emphasis on slope in the hot dust component – we need a sample that provides appropriate numbers of high-redshift quasars with observational data that cover the typical “1 $\mu m$ inflection” in the quasar SEDs and sample the onset of the hot dust emission. In addition, the individual SEDs used to construct the SDSS template have been corrected for host galaxy contributions (see Richards et al. (2006) for details) which has the largest effect ($\sim 35\%$ host contribution) in the rest frame NIR where the assumed elliptical host SED peaks.

In order to build template SEDs that cover higher redshifts at various luminosities, we here
use as a starting point the DR7 SDSS quasar sample presented by Shen et al. (2011). These authors also provide their quasar table matched with the preliminary data release from the WISE (Wright et al. 2010) MIR survey. This results in \( \sim 36000 \) quasars with SDSS optical photometry and WISE MIR detections in three bands (3.4, 4.6, 12 \( \mu \)m; we here do not consider the 22 \( \mu \)m band in which many objects are not detected). We further limited the objects to redshifts greater than 2.5 so that the WISE photometry samples the hot dust part of the rest-frame quasar SED. From the remaining sources we then created mean SEDs in a fairly straightforward manner by first de-redshifting the sources into the rest frame, then interpolating them linearly in log space onto a common wavelength grid, normalizing them at 1 \( \mu \)m (rest frame) and eventually calculating the mean for various subsamples. We then compared these mean SEDs with our sample (Fig. 2). Specifically, we searched for trends with increasing redshift (at fixed luminosity) or with luminosity (at fixed redshift). A few important findings are:

- We see quite a large spread in SED shapes for our sample as well as in the comparison samples after normalization, which results in substantial error bars (here: mean absolute deviation). Such a spread of quasar SEDs was also seen by e.g. Elvis et al. 1994 and Richards et al. 2006 in their studies.
- No trend (within the errors) is observed when increasing the luminosity over 2 orders of magnitude \( (\sim 10^{45}-10^{47}) \) while keeping the redshift bin fixed \( (2.5 < z < 3) \).
- Equally no trend (within the errors) can be found with redshift between \( 2.5 < z < 4 \) when using only sources at comparable luminosity to the high-\( z \) objects.

This implies that the hot dust properties do not change significantly with either redshift or luminosity for the parameter space considered here. In fact, the diversity of individual quasar SEDs appears much greater than any differences between the sample mean values.

We stress, however, that this study and the results presented here have to be considered preliminary. We are currently looking into expanding the observational data base for the quasars by including NIR photometry from the UKIDSS survey. This will allow us to expand this study to even lower redshifts while still appropriately sampling the hot-dust part of the SED. Also, no correction for host galaxy contributions has been performed at this point which could be especially important for the lower luminosity objects. Such a correction could potentially influence the spectral shape in the NIR where the stellar population of an elliptical galaxy of old or intermediate age is brightest.

In fact, in a recent MIR interferometric study, Kishimoto et al. (2011) report a steepening of the radial dust distribution in the innermost few parsec with increasing luminosity. In the SEDs this would translate into a steeper NIR spectral slope for objects at higher luminosity which indicates that a careful accounting of the host galaxy contribution may prove to be important for the less luminous sources.

### 3. Far-infrared emission powered by star formation

About 30\% of the known luminous \( z \sim 6 \) quasars are detected at 250 GHz and/or in CO (e.g. Bertoldi et al. 2003; Wang et al. 2008). Such studies suggest 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.

However, for the vast majority of high-redshift objects we lack full FIR/sub-mm spectral energy distributions (SEDs). Far-infrared luminosities \( (L_{\text{FIR}}) \) and dust masses \( (M_{\text{dust}}) \) are commonly determined using single photometric measurements (typically at 250 GHz) and applying standard values for the dust temperature as determined from lower redshift objects. But the questions remains how far these assumptions are appropriate for the high-redshift objects.
Figure 2. Comparison of normalized SEDs. In both panels the black points indicate the observed photometry for our $z > 5$ sample (here 68 individual sources are shown). The black squares represents a mean SED for our sample created in a similar fashion as for the comparison SEDs. Top: Our sample compared with mean SEDs for various luminosity intervals but a common redshift regime $2.5 < z < 3.0$. We give the luminosity intervals and number of objects used to create a specific SED in the plot. Bottom: Same as above, but now for a fixed luminosity, and creating the mean SEDs for various redshift intervals.
From our new photometry providing full SED information in the rest frame wavelength range 0.5 – 80 µm, we have discovered seven quasars at z > 5 with considerable FIR excess emission, including SDSS J1148+5251 for which strong FIR and mm emission has been reported previously (e.g. Bertoldi et al. 2003, Beelen et al. 2006). In order to extract additional information from the SEDs, we fitted the observed photometry with a linear combination of a power-law in the UV/optical/NIR (emission from the accretion disk), a clumpy torus model (AGN heated dust from Höning & Kishimoto (2010)), and a modified black body (starburst-powered excess dust emission). The emissivity value $\beta$ for this last component was fixed to a value of 1.6 to be comparable to previous studies at high z. In all cases the additional FIR component was required to describe the observed SEDs at the longest wavelengths (see Fig. 3 for a few examples). These SED fits also allow us to determine quantitative parameters: first, the scaling of the torus dust emission can be converted into the bolometric luminosity required to power the observed emission (Höning & Kishimoto 2010). For the sources considered here we find $L_{\text{bol}} = 1 - 5 \times 10^{47}$ erg/s using this approach. These bolometric luminosities translate into dust sublimation radii of $\sim 3 - 5$ pc. We also see that in the combined fits, torus models with steep radial dust distributions are preferred, indicating that most of the dust resides close to the nucleus. Integrating only the FIR excess component between 8 and 1000 µm we determine luminosities of $\gtrsim 10^{13} L_\odot$. If we identify this component as being powered by star formation then we observe star formation rates of the order of a few times $10^3$ solar masses per year in these early quasar host galaxies. For SDSS J1148+5251 the star-formation rate we determine from the SED fits is consistent with the results from a [CII] imaging study (Walter et al. 2009). These spatially resolved observations also show that the bulk of the detected star formation takes place in the innermost 1.5 kpc of the host galaxy.

One interesting fact related to the FIR excess emission is that the temperature of this component in all sources is fairly high ($T \sim 65$ K), much higher than the $T \sim 45$ K typically found for lower redshift objects (e.g. Beelen et al. 2006). This latter value is commonly used to extrapolate from the 250 GHz measurements in high-redshift quasars (e.g. Wang et al. 2008). Since the determination of dust masses is quite sensitive to the temperature of the dust, the measured difference in FIR temperatures could potentially have an impact on the dust masses derived for the high-redshift quasars.

Our multi-wavelength imaging allows us to check for possible confusion with other (lower redshift) FIR bright sources which could contribute in the large SPIRE beams and mimic the higher FIR dust temperatures. No such confusion problems could readily be identified, at least on scales of a few arc seconds. We might also have to consider quasar heating of the dust as a possible source to raise the temperature of FIR emitting dust. The very luminous AGN puts out copious amounts of radiation which in principle might be able to heat dust in the host galaxy to the temperatures we observe. In such a case, only some fraction of the FIR luminosity will actually be powered by star formation and in our calculations above we would overestimate the star-formation rates in these objects. A more detailed analysis of these highly interesting sources is currently underway (Leipski et al. 2012, in preparation) and follow-up strategies have been initiated.

4. Summary
We present first results from our Herschel and Spitzer observations of $z > 5$ quasars. We find that existing quasar templates do not match the amount of hot dust emission observed in almost all high-z quasars. Using the latest SDSS quasar catalogue including data from the WISE MIR survey we do not detect any significant trends in the shape of the NIR SED when considering mean SEDs at various redshifts and luminosities. Our full SED coverage in the infrared reveals considerable FIR excess emission in seven objects. If powered by star formation, the FIR luminosities determined from SED fitting indicate star-formation rates of thousands of...
Figure 3. Full optical through infrared SEDs of four sources showing FIR excess emission with high temperatures. In order to disentangle AGN and starburst powered emission, the photometry has been fitted by a linear combination of three components: a power-law in the UV/optical/NIR (dotted line), a clumpy torus model (dashed line), and a modified black body (long-dashed line). The blue solid line shows the total fit. For all sources shown here, the temperature of the FIR component is $T \sim 65$ K. Note also that compared to Fig. 1 the AGN dominated MIR dust emission in SDSS J1148+5251 is much better described by this model, as is the overlap region of the AGN and the starburst “bump”.

solar masses per year. Furthermore, the FIR emission in these objects shows unusually high temperatures ($\sim 65$ K as opposed to 45 K at lower $z$). The analysis on these aspects is ongoing.

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