Demystifying the Diverse IR SEDs of Type-1 AGNs from $z \sim 0$ to $z \sim 6$

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AGN Spectral Energy Distribution (SED)

Elvis+1994
AGN Spectral Energy Distribution (SED)

Elvis+1994

accretion disk

torus

-800-1800 K
~200-600 K
< 100 K

Hot
Warm
Cold

3 um
20 um
1.3 um

Urry & Padovani 1995
The quasar SED seems universal...

Elvis+1994
47 low-z quasars

Richards+2006
259 quasars

Shang+2011
85 quasars with new data

Scott & Stewart 2014
237 sources
761 sources

Leipski+2014
24 z=5-6 quasars
w/ Herschel detections
We are here
(hot-)dust-free quasars

Jiang+2010

redshift

\(Z=6.08\)

\(Z=5.85\)
hot-dust-obscured galaxies

redshift

(hot-)dust-free quasars

Tsai+2015

Jiang+2010
hot-dust-obscured galaxies

extremely red quasars

(red-)dust-free quasars

Jiang+2010

Tsai+2015

Hamann+17

(Norm QSO1

Power-law component

Normal QSO1

J0005-0006

J0303-0019

(Z=5.85)  (Z=6.08)
hot-dust-obscur ed galaxies

extremely red quasars

(mid-)dust-free quasars

mid-IR warm-excess AGN

Xu+2015
hot-dust-obscurded galaxies  

extremely red quasars  

redshift  

(hot-)dust-free quasars  

mid-IR warm-excess AGN  

Peculiar AGNs only at high-z?  
Can be reconciled with low-z objects?  
What causes these SED variations?
Smooth: Pier & Krolik 92, Loska+ 93, Rowan-Robinson+ 93, Granato & Danese 94, Schartmann+ 05, 06, Fritz+ 06, Jud+17

Clumpy: Rowan-Robinson 1995, Heymann & Siebenmorgen 2012, Stalevski+ 12, 16, Cat3D (Honig+ 06), RADMC (Dullemond & van Bemmel 05), Schartmann+ 2008, Clumpy (Nenkova+ 2008)

Smooth + Clumpy: Siebenmorgen+15

Addition of polar dust:: Honig+17, Stalevski+17
Smooth: Pier & Krolik 92, Loska+ 93, Rowan-Robinson+ 93, Granato & Danese 94, Schartmann+ 05, 06, Fritz+ 06, Jud+17

Clumpy: Rowan-Robinson 1995, Heymann & Siebenmorgen 2012, Stalevski+ 12, 16, Cat3D (Honig+ 06), RADMC (Dullemond & van Bemmel 05), Schartmann+ 2008, Clumpy (Nenkova+ 2008)

Smooth + Clumpy: Siebenmorgen+15

Addition of polar dust: Honig+17, Stalevski+17

Too many degeneracies in the current radiative transfer models for AGN IR emission...
What are the ranges of AGN intrinsic IR SED variations?
Two kinds of dust-deficient quasars

- **Hot-dust-deficient quasars** (lower Eddington ratio)
  - Z<0.5 PG sample: ~17-22%
  - Z~0.5-2.5 LoCuSS sample: ~4%
  - Z~5-6.5 Leipski sample: ~16%
- **Warm-dust-deficient quasars** (higher AGN luminosity)
  - Z<0.5 PG sample: ~14-17%
  - Z~0.5-2.5 LoCuSS sample: ~2%
  - Z~5-6.5 Leipski sample: >14%~50%

*Lyu, Rieke & Shi 2017*
Dust-deficient quasars at z>5

SEDs of the so-called “dust-free” quasars

Stacked SED of Herschel non-detected z>5 quasars

HDD template
PG 0049+171
(the most HDD case in the PG sample)

Stack of Herschel non-detected z>5 quasars
(Leipski+2014)

Lyu, Rieke & Shi 2017
What about Seyfert nuclei?

aka, relatively low-luminosity AGNs
with $L_{AGN} \sim 10^8 - 10^{11} L_{sun}$

(for quasars, $L_{AGN} \sim 10^{11} - 10^{14} L_{sun}$)
Composite SED of Seyfert-1 nuclei

~30 low-z Seyfert-1 nuclei observed by SDSS and Spitzer/IRS without evidence of star-formation in the mid-IR. Photometry data are compiled from XMM-newton/Chandra, GALEX, SDSS, 2MASS, WISE, Spitzer/IRS

J. Lyu & G. Rieke 2018
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J. Lyu & G. Rieke 2018
AGN polar dust emission has been indeed observed!

Mid-IR interferometry observations of **type-1 AGN** in **NGC 3783** by **Hoenig et al. 2013**
(Also see e.g., Raban+2009, Hoenig+2012, Tristram+2014, Lopz-Gonzaga+2016, Leftley+2018)

~30 low-z Seyfert-1 nuclei observed by SDSS and Spitzer/IRS without evidence of star-formation in the mid-IR. Photometry data are compiled from XMM-newton/Chandra, GALEX, SDSS, 2MASS, WISE, Spitzer/IRS

*J. Lyu & G. Rieke 2018*
Let’s build an reddened type-1 AGN model...

1. Accretion disk + torus (a face-on viewpoint) described by intrinsic AGN templates:
   Normal, WDD, HDD from Lyu et al. 2017a, b

2. Possible obscuration by an extended dust component
   Radial density profile \( \rho(r) \propto r^{-\alpha}, \quad r_{\text{in}} < r < r_{\text{out}} \)
   Classical silicate:graphite mixture with grain size distribution \( \text{dn}/\text{da} \sim a^{-3.5} \) but allowing \texttt{a\_max} and \texttt{a\_min} to be changed

3. 1-D radiation transfer calculations with the DUSTY (Ivezic et al. 2017) code
Reproducing the observations of NGC 3783
(the first type-1 AGN with robust polar dust emission constraints)

Geometry
Density profile: $\rho(r) \sim r^{-0.5}$
Outer-to-inner radius $r_{\text{out}}/r_{\text{in}} = 500$
Inner Boundary $T_{\text{in}} = 1500 \text{ K}$

Grain properties
Standard ISM mixture (sil:gra=0.53:0.47)
Standard grain size distribution $p=3.5$
Larger size cutoffs $a_{\text{min}} = 0.04 \text{ um}$, $a_{\text{max}} = 10 \text{ um}$

High-spatial-resolution data adopted from Prieto+2010, Garcia-Gonzalez+2016

J. Lyu & G. Rieke 2018
Reproducing the observations of NGC 3783
(the first type-1 AGN with robust polar dust emission constraints)

Three known type-1 AGNs with the detections of Mid-IR polar dust emission

<table>
<thead>
<tr>
<th>Name</th>
<th>F(polar)/F(total) at lambda ~ 10 microns</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mid-IR interferometry</td>
<td>our SED analysis</td>
</tr>
<tr>
<td>NGC 3783</td>
<td>~60-80%</td>
<td>~75%</td>
</tr>
<tr>
<td></td>
<td>(Hoenig et al. 2013)</td>
<td></td>
</tr>
<tr>
<td>NGC 4507</td>
<td>~75%</td>
<td>~78%</td>
</tr>
<tr>
<td></td>
<td>(Lopez-Gonzaga et al. 2016)</td>
<td></td>
</tr>
<tr>
<td>ESO 323-77</td>
<td>~35%</td>
<td>~30%</td>
</tr>
<tr>
<td></td>
<td>(Leftley et al. 2018)</td>
<td></td>
</tr>
</tbody>
</table>
The Low-z Seyfert-1 sample with AGN-dominated MIR emission

Nearby type-1 AGNs with subarcsec-resolution mid-IR observations

- A subset of the Asmus et al. (2014) sample with Sy 1-1.5
- No extended mid-IR emission by comparing the ground-based subarcsec 10-12 micron photometry and the WISE W4 (~12 arcsec FWHM) flux

Broad-line AGNs that observed by SDSS and Spitzer/IRS

- FWHM(H\(\alpha\)) > 1200 km/s from optical spectral decomposition
- 11.3 PAH EW < 0.1 micron & star-forming (SF) contribution at 5-15 micron < 5%

In total, 64 type-1 nuclei with weak evidence of mid-IR SF at z=0.002-0.2
Reproducing the IR SEDs of individual Seyfert-1 nuclei

Photometry data from 2MASS, WISE, Spitzer, AKARI, Herschel, etc.

3-component SED model: AGN + stars (+ SF_dust)

Two parameters for the SED shape of the AGN Component:
1) intrinsic type
2) optical depth, $\tau_{\lambda}$
(everything else follows NGC 3783)

J. Lyu & G. Rieke 2018
The vast majority have very good fittings

~80% of the sample have $\tau_v \leq 2$

~30% of the sample are directly matched by the intrinsic templates

Reproducing the IR SEDs of individual Seyfert-1 nuclei

J. Lyu & G. Rieke 2018
Why could this simple model work?!

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\[ \rho(r) \propto r^{-\alpha}, \quad r_{\text{in}} < r < r_{\text{out}} \]

Why could this simple model work?!
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\[ F_{\text{tot},A} = F_1 + F_2 + F_3 + F_4 \]
Why could this simple model work?!

\[ F_{\text{tot},B} = N_1 F_1 + N_2 F_2 + N_3 F_3 + N_4 F_4 = 2F_1 + 4F_2 + 6F_3 + 8F_4 \]
Why could this simple model work?! 

$F_{\text{tot},B} = N_1 F_1 + N_2 F_2 + N_3 F_3 + N_4 F_4 = 2F_1 + 4F_2 + 6F_3 + 8F_4$

Once the radial distribution, $\rho(r)$, is settled, the SED of optically-thin dust emission does not care much about the geometry (along $\theta$ and $\phi$ directions), neither the observing angle!
Why could this simple model work?!

$F_{\text{tot, } B} = N_1 F_1 + N_2 F_2 + N_3 F_3 + N_4 F_4 = 2F_1 + 4F_2 + 6F_3 + 8F_4$

**total SED:** $F_\lambda \approx \int_{r_{\text{in}}}^{r_{\text{out}}} \rho(r) B_\lambda(r) dr$.

**total optical depth:** $\tau_V = \int_{r_{\text{in}}}^{r_{\text{out}}} \rho(r) C_{\text{ext, } V} dr = C_{\text{ext, } V} \int_{r_{\text{in}}}^{r_{\text{out}}} \rho(r) dr$

*Extinction efficiency of an LTE dust element*

*The amount of dust*
The dust environment of a typical Seyfert nucleus

Integrated optical depth
\[ \tau_v \sim 0 - 5 \]

Density profile:
\[ \rho(r) \sim r^{-0.5} \]

Large dust grains
\[ a_{\text{min}} \sim 0.04 \text{ um} \]
\[ a_{\text{max}} \sim 10 \text{ um} \]

Dust temperatures
Inner Boundary
\[ T_{\text{in}} \sim 1500 \text{ K} \]
Most common
\[ T_{\text{peak}} \sim 120 \text{ K} \]

For a \( L_{\text{AGN}} \sim 10^{11} L_{\odot} \) AGN in a \( M_{\text{star}} \sim 10^{11} M_{\odot} \) main-sequence galaxy, polar dust \( r_{\text{out}} \sim \text{a few} \times 10^2 \text{ pc} \)

The dust mass
Host ISM \(~ 10^8 M_{\odot} \)
AGN polar dust \(~ 10^5 M_{\odot} \)
AGN “torus” \(~ 10^3-10^5 M_{\odot} \) (???)
Do the SEDs of high-z type-1 AGNs behave similarly?
Extremely red quasars at $z \sim 2-3.4$

$L_{\text{AGN}} > 10^{13} L_{\odot}$; Strong outflow features

(Hamann+17)
Extremely red quasars at $z \sim 2-3.4$

Two parameters for the SED shape of the AGN Component:
1) intrinsic type: normal
2) optical depth, $\tau_V \sim 3.0$
(everything else follows NGC 3783)
AGNs with mid-IR warm-excess emission at z=0.7-2.3

(Xu+2015)

Two parameters for the SED shape of the AGN Component:
1) intrinsic type: normal
2) optical depth, $\tau_v \sim 0-3$

(everything else follows NGC 3783)
Hot dust-obscured galaxies at z~2-4

Density profile $r^{-0.5} \rightarrow r^{-1.5}$
Outer-to-inner radius $r_{out}/r_{in} = 500 \rightarrow 5000$
(dust grains properties and $T_{in}$ follow NGC 3783)
Hot dust-obscured galaxies at $z\sim2-4$

Density profile $r^{-0.5} \rightarrow r^{-1.5}$
Outer-to-inner radius $r_{out}/r_{in} = 500 \rightarrow 5000$
(dust grains properties and $T_{in}$ follow NGC 3783)

ALMA observations of W2246-0526 shows the strikingly uniform, highly turbulent ISM over the entire galaxy.
Hot dust-obscured galaxies at z<0.5

Density profile \( r^{-0.5} \rightarrow r^{-1.5} \)
Outer-to-inner radius \( r_{\text{out}}/r_{\text{in}} = 500 \rightarrow 5000 \)
(dust grains properties and \( T_{\text{in}} \) follow NGC 3783)

Similar model explains the low-z AGNs with hot-dust-excess emission
Multi-wavelength spatially-resolved study of nearby AGNs with characteristic SEDs: X-ray, optical-IFU, JWST/MIRI, ALMA, etc.

Flux surface density as a function of $\lambda$ for the polar dust component (based on Lyu & Rieke 2018)

$r_{\text{in}} = \text{dust sublimation radius}$
Take-home messages

1. AGN intrinsic IR variations: normal, WDD and HDD;

(see more in Lyu, Rieke & Shi 2017; Lyu & Rieke 2017)

2. Regardless of luminosity and redshift, a two-free parameter model is good enough to reconcile the IR SEDs of most type-1 AGNs:

   intrinsic AGN types, $\tau_V$ of the polar dust component;

Most, if not all, high-z AGNs with abnormal SED features have low-z counterparts;

3. In the first order, the AGN dust environment has two components:

   the torus ($\sim$1-10 pc) – determined by the BH accretion processes;

   the extended polar dust component ($\sim$0.1-1 kpc) – controlled by feedback from AGN and/or host galaxy

(see details in Lyu & Rieke 2018)

Download AGN templates at https://github.com/karlan/AGN_templates

Get a digital poster here →
Backup A: observed size

*Hoenig et al. 2013*

Nuclear dust distribution at 8-13 micron is $\sim 20-70$ r$_{in}$ for NGC 3783

*Our model*

The polar dust component has r$_{out}$ $\sim 500$ r$_{in}$

Wien’s displacement law $\lambda_{\text{peak}} \cdot T \sim 2900 \, \mu m \cdot K$

*J. Lyu & G. Rieke 2018*
Backup B: X-ray obscuration and polar dust extinction

![Graph showing X-ray obscuration and polar dust extinction](image-url)
Backup C: model parameters
Table 1. DUSTY model setup

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Label</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_{\text{in}}$ temperature</td>
<td>$T_{\text{in}}$</td>
<td>2000 K, 1500* K, 1000 K</td>
</tr>
<tr>
<td>density profile</td>
<td>$\alpha$</td>
<td>0, 0.5*, 1, 1.5, 2</td>
</tr>
<tr>
<td>outer-to-inner radius</td>
<td>$Y$</td>
<td>50, 500*, 5000</td>
</tr>
<tr>
<td>silicate:graphite mixture</td>
<td></td>
<td>0:1, 0.53:0.47*, 1:0</td>
</tr>
<tr>
<td>maximum grain size</td>
<td>$a_{\text{max}}$</td>
<td>0.25, 2.5, 10*, 100</td>
</tr>
<tr>
<td>minimum grain size</td>
<td>$a_{\text{min}}$</td>
<td>0.005, 0.01, 0.05*, 0.1</td>
</tr>
<tr>
<td>input radiation SED</td>
<td></td>
<td>norm, WDD*, HDD</td>
</tr>
<tr>
<td>optical depth</td>
<td>$\tau_V$</td>
<td>0–10 with a step of 0.25</td>
</tr>
</tbody>
</table>

**NOTE**—We use * to indicate the reference parameters that adopted to demonstrate the influence of the output SEDs in Figure 2.
Backup D: model decompositions
Backup E: dust-free quasars

![Graph showing the relation between λL(λ) and λL(0.51μm)]

- Elvis template
- HDD template
- Jun & Im 2013 cut

![Graph showing the spectral energy distribution (SED) of three quasars: J0005-0006 (z=5.85), J0303-0019 (z=6.08), and J1411+1217 (z=5.93)]]

- Vf (W/cm^2)
- Wavelength (μm)
2/3 of the Palomar-Green quasar sample have good fits with 0.5-100 um residuals < 0.3 dex;

Near-IR Stellar contributions are consistent with the results from the image decomposition within 20%;

The SFRs based on the host IR luminosities are consistent with the results from mid-IR 11.3 aromatic features within < 0.3 dex.

Lyu, Rieke & Shi 2017
No luminosity dependence is found for HDD quasars. (see also, Hao et al 2010, 2011)

**WDD quasars support the covering factor vs. luminosity relation**
Backup F: The AGN properties of dust-deficient PG quasars

WDD quasars tend to have higher AGN luminosities
HDD quasars tend to have lower Eddington ratios

Lyu, Rieke & Shi 2017
Backup F: The AGN properties of dust-deficient PG quasars

WDD quasars tend to have higher AGN luminosities
HDD quasars tend to have lower Eddington ratios

K–S Probabilities of the HDD and WDD Quasars Against Normal Quasars

<table>
<thead>
<tr>
<th>Property</th>
<th>HDD</th>
<th>WDD</th>
<th>HDD+WDD</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{\text{AGN}}$</td>
<td>0.363</td>
<td>0.057$^a$</td>
<td>0.664</td>
</tr>
<tr>
<td>$M_{\text{BH}}$</td>
<td>0.762</td>
<td>0.140</td>
<td>0.315</td>
</tr>
<tr>
<td>$L_{\text{AGN}}/L_{\text{Edd}}$</td>
<td>0.025</td>
<td>0.688</td>
<td>0.074</td>
</tr>
<tr>
<td>$S_{10}$</td>
<td>0.009</td>
<td>0.002</td>
<td>0.001</td>
</tr>
</tbody>
</table>

WDD quasars tend to have higher AGN luminosities
HDD quasars tend to have lower Eddington ratios
Multi-wavelength spatially-resolved study of nearby AGNs with characteristic SEDs: X-ray, optical-IFU, JWST/MIRI, ALMA, etc.

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