The Dust and Cloud Distribution of the Torus of NGC 1068

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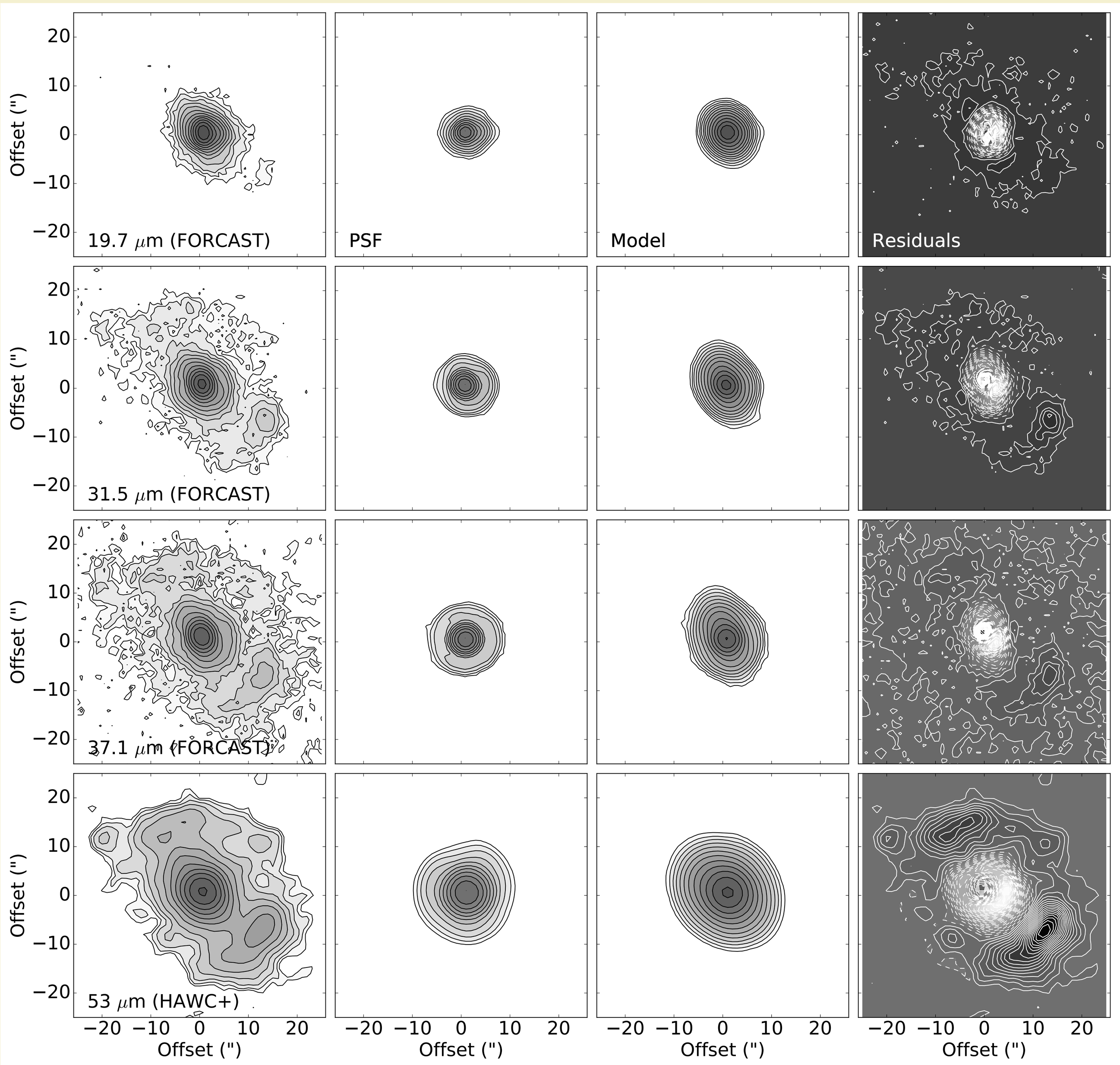
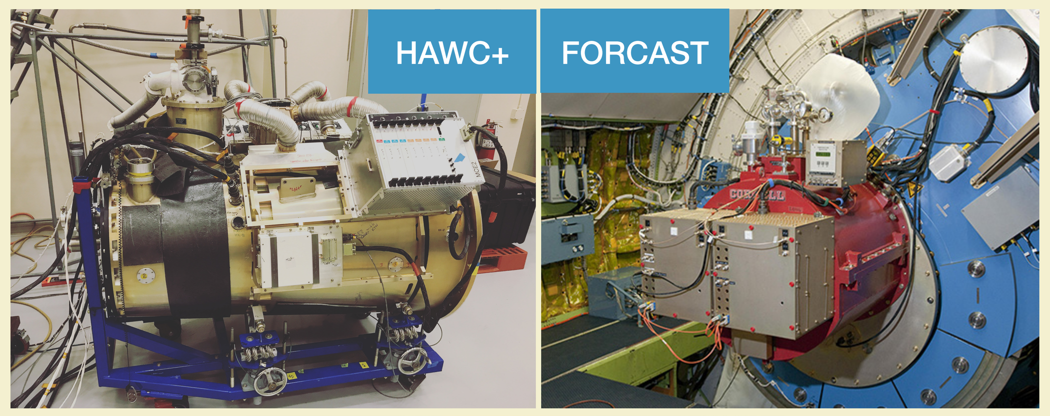
The 8-13 µm (mid-infrared; MIR) spectral range has proven to be exceptionally rich in spectral features that can be used to characterize the dust emission properties of active galactic nuclei (AGN). At longer wavelengths (> 20 µm), the moderate angular resolution (>10”) observations available by space-based telescopes have made the characterization of nearby AGN very challenging. This is because of the large contribution of the host galaxy at longer wavelengths and the difficulties to isolate the AGN emission from other components within these moderate angular resolution observations. From the ground, IR observations at wavelengths > 20 microns are impossible due to the atmosphere. Thus, the cold dust of the torus is poorly constrained as well as the turn-over of the torus emission. The Stratospheric Observatory For Infrared Astronomy (SOFIA) has opened a new window to explore AGN in the range of 20-300 µm with angular resolutions < 10”. We here present newly 20-53 µm imaging observations using FORCAST and HAWC+ onboard SOFIA of NGC 1068 that, in conjunction with high-angular resolution 1-13 µm and sub-mm observations, allow us to characterize the obscuring torus. Using CLUMPY torus models, we inferred the best torus model parameters and we computed 2D images of the dust emission and cloud distribution at several wavelengths from 1 to 432 µm. We found that 1) the 1-20 µm wavelength range solely is not able to probe the full extend of the torus; 2) the turn-over of the torus emission occurs in the 30-40 µm which is sensitive to the detection of cold dust in the torus, and 3) the morphology of the dust emission in our 2D image at 432 µm is spatially coincident with the cloud distribution of the torus using 432 µm ALMA observations. We also found that the dust emission from our 2D clumpy torus image at 12 µm shows an elongated morphology perpendicular to the cloud distribution, and can produce comparable results to those observed using IR interferometry.

SOFIA Observations

NGC 1068 was observed as part of the Guaranteed Time Observations (GTO) of FORCAST and HAWC+ on the 2.7-m SOFIA. We made FORCAST observations using the dual-channel mode at 19.7 µm and 31.5 µm, and 37.1 µm. Total on-source times are ~450s per filter. PSF were estimated using Ceres with a FWHM of 2.4”, 2.8” and 2.9”. We made HAWC+ observations using the Lissajous scan mode at 53 µm with a total on-source time of 455s. PSF was estimated using Uranus with a FWHM of 4.9”.



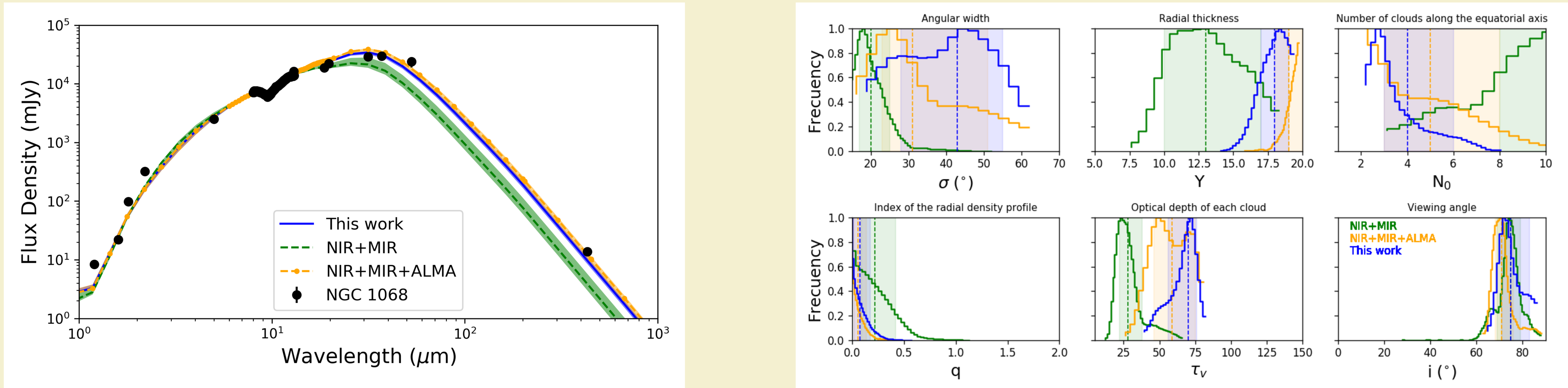
From left to right: NGC 1068 observations, scaled PSF, Model (PSF+2D Gaussian) of the central 20” x 20” (1.4 × 1.4 kpc²), and Residuals (NGC 1068– Model) at 19.7 µm, 31.5 µm, 37.1 µm and 53 µm from top to bottom, respectively. In all cases, the FOV is 50” x 50” (3.5 × 3.5 kpc²). NGC 1068, PSF and Model contours are shown in log(flux density [Jy]) from −2.0 to 1.5 in steps of 0.2. Residual contours are shown in flux density (Jy) from −0.4 Jy to 0.3 Jy in steps of 0.02 Jy. North is up and east is left.



Dust and Cloud distribution of the torus as a Function of Wavelength Coverage

We investigate the emission and distribution of dust of the torus of NGC 1068 using SED coverages. Our SED is constructed using 1-500 µm imaging and spectroscopic observations at sub-arcsecond and arcsecond resolution after taking into account extended emission by the host galaxy and ionization cones. SED coverage were divided into three: 1) 1-13 µm, labeled as ‘NIR+MIR’, 2) 1-13 µm and ALMA, labeled as ‘NIR+MIR+ALMA’, and 3) full SED from 1 µm to 500 µm using new SOFIA observations, labeled as ‘This work’. For each SED, we obtained the best inferred CLUMPY (Nenkova et al. 2008) torus model with their posteriors. Based on SED fitting, we found:

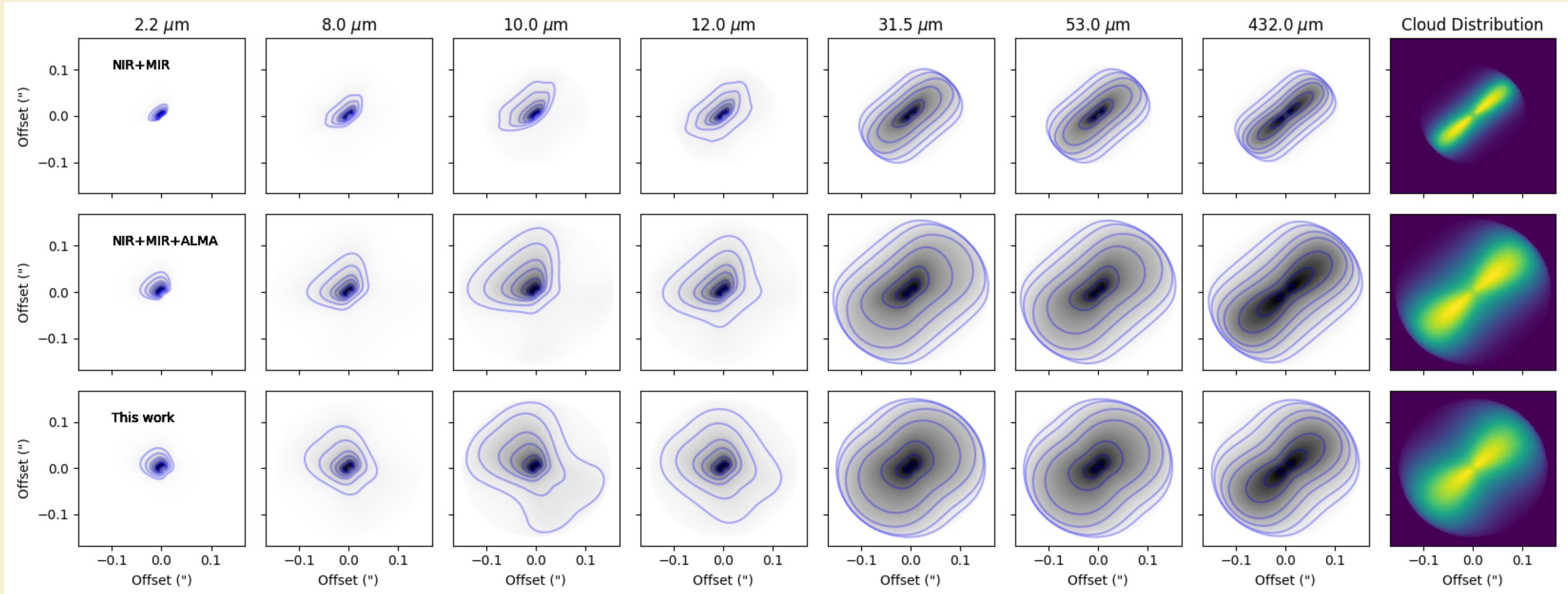
When CLUMPY torus model fitting is used with data only in the 1–20 µm wavelength range, (1) the torus is smaller and more compact (large q values) than the current resolved torus of ~10 pc diameter of NGC 1068 by the ALMA observations, and (2) the turnover of the torus emission peaks at shorter wavelengths than when the SED coverage includes observations at longer wavelengths. This result implies that 1–20 µm observations are not able to probe the full extent of the torus. Despite the angular resolution, 2.4”- 4.9” , SED fitting shows that the turnover of the torus emission occurs in the range of 30–40 µm, which corresponds to a characteristic temperature of 70–100 K. This result indicates that (a) the amount of cold dust and/or (b) the radiation from indirectly radiated clouds is substantial to shift the peak emission of the torus toward longer wavelengths.



Left: CLUMPY torus models inferred using different SED coverage. Right: Posterior distributions of the CLUMPY torus model parameters for the best inferred SED models. The shadowed region shows the 1–sigma uncertainty and the dashed lines show the best inferred model parameter value.

We use the radiative transfer code CLUMPY torus (Nenkova et al. 2008) to compute the surface brightness and cloud distributions of the dusty torus as a function of wavelength for each set of parameters from each SED coverage. We use the HyperCubes of AGN Tori (HYPERCAT; Nikutta et al., in preparation). HYPERCAT uses the CLUMPY torus models with any combination of parameters to generate physically scaled and flux-calibrated 2D images of the dust emission and distribution for a given AGN.

For all cases, the clouds are distributed in the equatorial plane with major differences in their torus sizes, angular widths, and radial density profile. These differences affect the morphology of the dust emission as a function of wavelength. We find that the 2.2 µm dust emission is concentrated on the inner edge of the torus where dust is directly radiated by the central engine, while the 8–12 µm dust emission is along the polar direction as the high opacity in the equatorial direction is absorbing most of the radiation from the central engine. At longer wavelengths, >30 µm, the dust emission is along the equatorial plane, where the 432 µm truly describes the bulk of dust distribution in the torus. when ALMA observations are compared with the 2D images produced by the 1–20 µm SED, the inferred torus model is smaller, more compact, and thinner, which supports the discussion above regarding the 1–20 µm observations, which underestimate the true size of the torus.

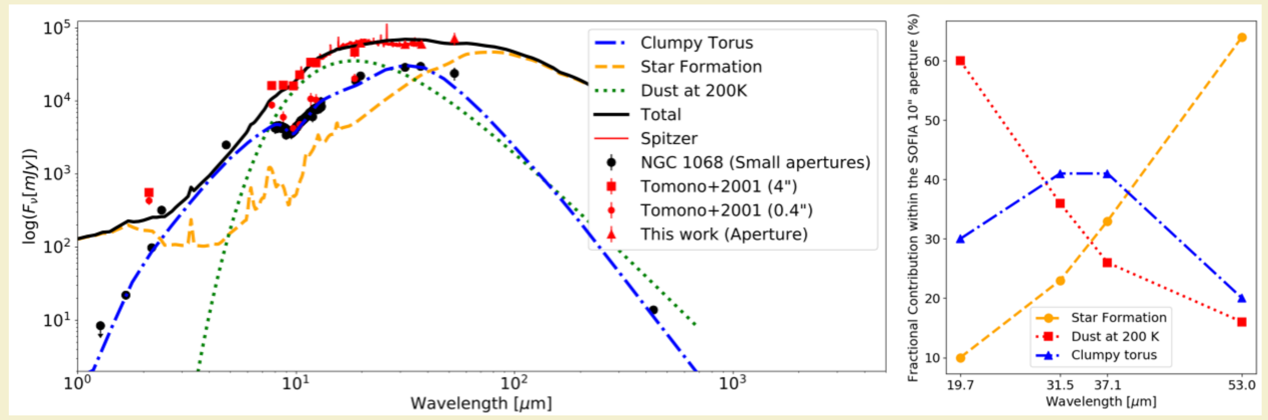


2D CLUMPY torus images of NGC 1068 generated using HyperCAT (Nikutta et al., in preparation) based on the several SED coverages. The first seven columns show the dust emission from 2.2 to 432 µm, while the last column shows the cloud distribution. Contours show the intensities at the levels of 0.05, 0.1, 0.2, 0.3, 0.5, 0.7, and 0.9 times the peak flux. In all cases, the model was scaled to a distance of 14.4 Mpc; North is up and East is left.

Spectral Decomposition

We perform an SED analysis and fit the SED of the nuclear emission using aperture and PSF-scaling photometric measurements, hereafter referred to as “large” and “small” aperture SEDs, respectively. The large aperture SED is composed of our 10″ aperture photometry in combination with *Spitzer* spectroscopic data taken from CASSIS. We also include the 2–20 µm photometry in a 4″ (280 pc) aperture using the Mid-Infrared Test Observation System on the 8.2 m Subaru Telescope by Tomono et al. (2001). The large aperture SED was fitted as the contribution of the best inferred of the CLUMPY torus model to the small aperture SED and a star formation component.

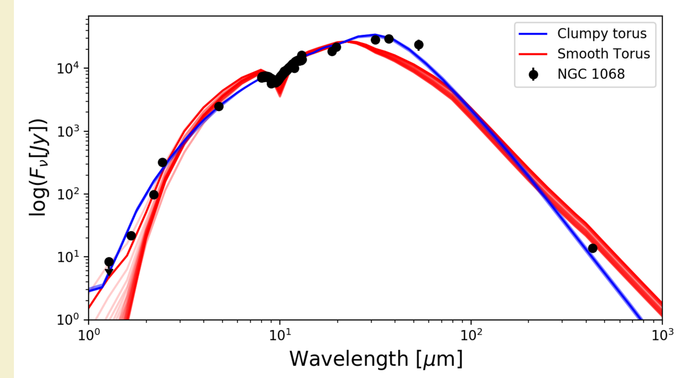
Based on our spectral decomposition within the 10″ (700 pc) nuclear aperture, the fractional contribution to the total flux of the star formation increases with increasing wavelength, from 10 ± 1% at 19.7 µm to 64 ± 3% at 53 µm. The dust emission from extended dusty structures modeled as a blackbody component with a characteristic temperature at 200 K decreases with increasing wavelength, from 60 ± 3% at 19.7 µm to 16 ± 1% at 53 µm. This extended emission, not associated with the torus, contributes >80% of the total flux in the 8–20 µm wavelength range and it is attributed to the N-S dust emission. The fractional contribution to the total flux of the torus emission shows a turnover in the range of 30–40 µm with a maximum fractional contribution to the total emission of 41 ± 2%, reaching a minimum of 20 ± 1% at 53 µm. The turnover of the torus emission in the range of 30–40 µm can be distinguished from (a) the expected peak emission at ~100 µm by star formation regions, and (b) the extended dust emission associated with the NLR at shorter wavelengths.



Left: spectral decomposition of the nuclear SED of NGC 1068. The large apertures (red dots and lines) were fitted using the star formation region (orange dashed line), the CLUMPY torus (blue dotted–dashed line), and a blackbody component at 200 K (green dotted line). The small aperture photometry and spectroscopy (black dots) were fitted simultaneously. The total model (black line) is shown. Right: fractional contribution to the total flux within the SOFIA 10″ aperture from the star formation (orange dashed line/ circle), dust at 200 K (red dotted line/square), and CLUMPY torus (blue dotted–dashed line/triangle) components.

CLUMPY vs. SMOOTH

We have also used smooth torus models (Efstathiou & Rowan-Robinson 1995) to fit the nuclear SED of NGC 1068. In general, the smooth torus models reproduce well the nuclear SED of NGC 1068, except for the FIR (20–60 µm) wavelength range. In this spectral range, the smooth torus models underestimate the measured nuclear fluxes. We note that if we force these models to fit the FIR range, then the smooth torus models overpredict the submillimeter fluxes by a factor of 10 or more, and the torus size increases to a few tens of parsecs. Thus, we use the MIR spectroscopic observations, i.e., the 10 µm silicate feature, and the ALMA observations to find the best fit of the smooth torus model.



Best-fit (solid line) and 1σ uncertainties (shadowed area) of the CLUMPY (blue) and smooth (red) torus models to the nuclear SED (black dots) of NGC 1068.

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