SOFIA/FORCAST Resolves 30 - 40 $\mu$m Extended Dust Emission in Nearby Active Galactic Nuclei

Lindsay Fuller,1⋆, Enrique Lopez-Rodriguez2, Chris Packham,1,3, Kohei Ichikawa1,3,4,5,6, Aditya Togi1,7, Almudena Alonso-Herrero8,1, Cristina Ramos-Almeida9,10, Tanio Diaz-Santos11, N. A. Levenson12, James Radomski2

1 The University of Texas at San Antonio, One UTSA Circle, San Antonio TX, 78249, USA
2 SOFIA Science Center, NASA Ames Research Center, Moffett Field, CA 94035, USA
3 National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan
4 Department of Astronomy, Columbia University, 550 West 120th St, New York, NY 10027, USA
5 Frontier Research Institute for Interdisciplinary Sciences, Tohoku University, Sendai, Miyagi 980-8578, Japan
6 Astronomical Institute, Tohoku University, Aramaki, Aoba-ku, Sendai, Miyagi 980-8578, Japan
7 St. Mary’s University, 1 Camino Santa Maria, San Antonio, TX, 78228, USA
8 Centro de Astrobiología (CSIC-INTA), ESAC Campus, E-28692 Villanueva de la Cañada, Madrid, Spain
9 Instituto de Astrofísica de Canarias, Calle Vía Láctea, s/n, E-38205, La Laguna, Tenerife, Spain
10 Departamento de Astrofísica, Universidad de La Laguna, E-38206, Tenerife, Spain
11 Núcleo de Astronomía de la Facultad de Ingeniería, Universidad Diego Portales, Av. Ejercito Libertador 441, Santiago, Chile
12 Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD, 21218, USA

Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT
We present arcsecond-scale observations of the active galactic nuclei (AGNs) of seven nearby Seyfert galaxies observed from the Stratospheric Observatory For Infrared Astronomy (SOFIA) using the 31.5 and 37.1 $\mu$m filters of the Faint Object infraRed CAmera for the SOFIA Telescope (FORCAST). We isolate unresolved emission from the torus and find extended diffuse emission in six 37.1 $\mu$m residual images in our sample. Using Spitzer/IRS spectra, we determine the dominant mid-infrared (MIR) extended emission source and attribute it to dust in the narrow line region (NLR) or star formation. We compare the optical NLR and radio jet axes to the extended 37.1 $\mu$m emission and find coincident axes for three sources. For those AGNs with extended emission coincident with the optical axis, we find that spatial scales of the residual images are consistent with 0.1 - 1 kpc scale distances to which dust can be heated by the AGN. Using previously published subarcsecond 1 - 20 $\mu$m imaging and spectroscopic data along with our new observations, we construct broadband spectral energy distributions (SEDs) of the AGNs at wavelengths 1 - 40 $\mu$m. We find that three AGNs in our sample tentatively show a turnover in the SED between 30 - 40 $\mu$m. Using results from CLUMPY torus models and the Bayesian inference tool BAYESCLUMPY, we find that the posterior outputs for AGNs with MIR turnover revealed by SOFIA/FORCAST have smaller uncertainties than AGNs that do not show a turnover.

Key words: active – nucleus – Seyfert

1 INTRODUCTION

Infrared (IR) emission from active galactic nuclei (AGNs) is largely attributed to an optically and geometrically thick toroidal dust structure that primarily intercepts optical and ultraviolet (UV) emission from the central accreting black hole and re-emits in IR wavelengths. According to the unified model (Antonucci 1993; Urry & Padovani 1995), an approximate edge-on view of the thick dust torus fully obscures the center in Type 2 AGNs, while a more pole-on view allows a direct line of sight into the center of Type 1 AGNs. See Netzer (2015); Ramos Almeida & Ricci (2017) for recent reviews on nuclear obscuration.

The AGN torus has been modeled assuming a smooth dust distribution (Pier & Krolik 1992, 1993; Granato & Danese 1994; Siebenmorgen et al. 2004; Schartmann et al. 2006).
and, more recently, a clumpy distribution (Nenkova et al. 2008a; Hönig et al. 2010). The latter more accurately describes imaging (Packham et al. 2005; Radomski et al. 2008), interferometry (Jaffe et al. 2004; Tristram et al. 2007; Raban et al. 2009; Burtscher et al. 2013; Tristram et al. 2014), and recent ALMA observations of NGC 1068 (García-Burillo et al. 2016), which establish a parsec-scale torus. The clumpy models of Nenkova et al. (2008a) have been used extensively to derive torus model parameters (Ramos Almeida et al. 2009, 2011; Alonso-Herrero et al. 2011; Ichikawa et al. 2015; Martínez-Paredes et al. 2017). The radial size of the torus gives insight as to the wavelength of peak IR emission (van Bennet & Dullemond 2003; Ramos Almeida et al. 2011; Asensio Ramos & Ramos Almeida 2013). However, due to a lack of high spatial resolution (< 1") observations beyond 20 µm, there has not yet been observational confirmation of the wavelength of peak flux density of the torus. Models suggest that the turnover of the torus emission is between 20 - 50 µm (Nenkova et al. 2008a; Hönig et al. 2010; Ramos Almeida et al. 2014). Using data from the 2.5-m Stratospheric Observatory For Infrared Astronomy (SOFIA), Fuller et al. (2016) (hereafter F16) found that the wavelength of peak flux density generally does not occur at wavelengths less than 31.5 µm.

The SOFIA telescope provides the best spatial resolution (∼ 3.4" at 31 µm) to date for observations between ∼ 20 - 70 µm. However, SOFIA cannot resolve the subarcsecond-scale torus structure and contamination from other MIR sources is likely. Spectroscopic analysis of polycyclic aromatic hydrocarbon (PAH) emission features reveals that excess MIR emission in some AGNs can have a major contribution from star formation (SF; Clavel et al. 2000; Weedman et al. 2005; Buchanan et al. 2006; Tommasin et al. 2008; Ichikawa et al. 2012; Esquej et al. 2014). For example, Alonso-Herrero et al. (2014) found that PAH emission in six AGNs known to have nuclear star formation occurs at distances of ~ 60 - 420 pc.

There is also significant evidence for IR emission coincident with the narrow line region (NLR) in some AGNs. On subarcsecond scales, Hönig et al. (2012, 2013); Tristram et al. (2014); López-Gonzaga et al. (2016) detected MIR emission distributed in the polar regions of the nucleus of several Seyfert galaxies. On larger scales, Asmus et al. (2016) detected clear extended polar emission consistent with the NLR out to hundreds of parsecs for 18 AGN. Mason et al. (2006) found that MIR emission of NGC 1068 emanates from two separate components; the torus dominates emission < 1", but for apertures > 1", MIR emission is dominated by dust emission from the ionization cones. Likewise, Radomski et al. (2003) resolves 10.8 and 18.2 µm emission in NGC 4151 extending 3.5" in the direction of the NLR.

In this paper, we present the best spatial resolution 37.1 µm imaging data currently available for a sample of 7 bright Seyfert galaxies using the SOFIA telescope. Of those 7, we also obtained 31.5 µm imaging data for 3 AGN. We examine the turnover of emission from the obscuring torus, and also determine the source of extended emission for each AGN in our sample. To provide a description of the physical properties of the torus, we use the CLUMPY torus models of Nenkova et al. (2008a) with the Bayesian inference tool, BAYESCLUMPY (Asensio Ramos & Ramos Almeida 2009), to fit the IR (1 - 37.1 µm) nuclear SEDs. In Section 2 we describe the observations and data reduction; in Section 3 we explain our method of image analysis; in Section 4 we discuss the source of extended emission in our sample; in Section 5 we describe the model fitting and results; and Section 6 summarizes our analysis.

2 OBSERVATIONAL DATA

2.1 Sample Selection

The primary motivation of this study is to extend the wavelength range of AGN observations to 37.1 µm for use in modeling MIR emission around the active nucleus. Three sources (NGC 3081, NGC 3227, and NGC4388) were included in the study of F16 in the wavelength range between 1 - 31.5 µm. One source (NGC 4151) was not included in F16, but has been extensively studied from 1 - 18 µm (Ramos Almeida et al. 2009; Alonso-Herrero et al. 2011; Ichikawa et al. 2015). Three sources (Mrk 3, NGC 1275, and NGC 2273) were chosen based on their inclusion in the N-band spectral atlas of Alonso-Herrero et al. (2016).

The seven Seyfert galaxies presented in this work are part of an on-going AGN survey within the 30 - 100 µm range using SOFIA (Proposal ID: #02_0035, #04_0048, #06_0066 PI: Lopez-Rodriguez). The AGN survey includes bright, nearby Seyfert 1 and 2 galaxies in a flux-limited sample with nuclear fluxes > 500 mJy at 31.5 µm, and bolometric luminosities 43 < log Lbol[erg s⁻¹] < 46. In the current sample, we selected galaxies with subarcsecond-resolution N-band spectroscopy from the literature. The sample is not representative, and the high-resolution spectra are included in order to represent only emission from the torus surrounding the AGN. The basic properties of the sample are given in Table 1.

2.2 Observations

We obtained photometric observations (Proposal ID: #04_0048, PI: Lopez-Rodriguez) using the 31.5 and 37.1 µm filters of the Faint Object Infrared CAmera for the SOFIA Telescope (FORCAST; Herter et al. 2012) on the SOFIA airborne observatory (Young et al. 2012). FORCAST is a dual-channel camera and spectrograph, operational from 5 to 40 µm. The short wavelength channel (SWC; λ < 25 µm) and the long wavelength channel (LWC; λ > 25 µm) have a 256 × 256 pixel² array and can be used in simultaneous dual channel mode or individually. The 0.768"/pixel scale gives an effective field of view (FOV) of 3.4 × 3.2 arcmin². Our data was taken with the 31.5 µm (Δλ = 5.7 µm) and the 37.1 µm (Δλ = 3.3 µm) filter used with the LWC in single channel mode.

Observations were made using the two-position chop-nod (C2N) method with symmetric nod-match-chop (NMC) to remove time-variable sky background and telescope thermal emission, and to reduce the effect of 1/f noise from the array. Data were reduced using the FORCAST_REDUX pipeline version 1.1.3 as described in Herter et al. (2012). NGC 1275 was observed twice during the cycle, once in February 2016 and once in September 2016. We present the results as an average of the two observations. A summary of observations,
including the FWHM of the AGN and point spread functions (PSFs), are given in Table 2. The variation in the 31.5 \( \mu \)m standard FWHM was not found to be wavelength dependent, but rather due to variability in seeing or tracking on SOFIA.

2.3 Point Spread Functions

The PSF was taken to be the average of multiple observations of a single standard star for a given observing date in the corresponding filter. On 17 February 2016 two separate standards were observed at 37.1 \( \mu \)m. For that data, the standard star observed in the time frame closest to the AGN observation was the averaged standard used for the PSF. The radial profiles of the AGN observations and their associated PSFs are shown in Figure 1.

To account for host galaxy contamination in the nuclear fluxes, we used the PSF scaling method described in F16. The total flux density is measured in an 18" diameter circular aperture (an 18" aperture is used in the flux calibration to ensure as close to 100% of the standard star flux is measured). The PSF of the observed, scaled to the peak of galaxy emission, represents the maximum contribution from the unresolved torus component. The scale of the PSF is reduced until the subtraction of the PSF from the source image (hereafter called the residual) yields a smooth profile. Due to MIR sky variability on the order of \( \sim 10\% \), we used a 10% increment in scaling the PSF as in previous works (e.g. Radomski et al. 2002, 2003; Packham et al. 2005; Levenson et al. 2009; Ramos Almeida et al. 2009, 2011; García-Bernete et al. 2015; Fuller et al. 2016). Table 3 gives the total flux within an 18" aperture (\( F_{\text{tot}} \)), the total percent the PSF was scaled (\( \% \text{PSF}_{\text{scale}} \)), and the PSF-scaled flux (\( F_{\text{PSF}} \)) which represents the flux from the unresolved torus component. The described method yielded inconsistent results for NGC 3081. Due to this and the low signal-to-noise ratio (SNR), we use \( F_{\text{tot}} \) as an upper limit. This is discussed further in Section 4.4.

To estimate photometric uncertainty, we first determined the variability in individual calibration factors for the standard stars associated with a given observation date, which was \( \sim 6\% \). We determined that the uncertainty due to a variable PSF obtained by cross-calibrating the standard stars is \( \sim 7\% \). Additional uncertainty in unresolved fluxes determined from the PSF subtraction was estimated as 10%. The total uncertainties were estimated by adding these contributions in quadrature.

Following the method of F16 to test the results of the PSF scaling, we performed a spectral decomposition analysis of Spitzer/IRS spectra. The routine DeblendIRS (Hernán-Caballero et al. 2015) uses a combination of three templates to represent total MIR emission from Spitzer/IRS; these emission sources are 1) AGN, 2) star formation (PAH), and 3) diffuse host galaxy emission. See also García-Burillo et al. (2016) for an example of DeblendIRS applied to Spitzer spectra of Seyfert galaxies. The routine has templates for each component and outputs the combination of templates with the lowest \( \chi^2 \). The Spitzer spectra generally span 5 - 38 \( \mu \)m, however many of the templates are from high redshift sources, so their spectra reach 38 \( \mu \)m in the observed frame, but not in the rest frame. For this reason only 20 of 189 AGN templates were applicable to observations at 37.1 \( \mu \)m. Due to the reduced number of templates, the decomposition showed a reduced \( \chi^2 \) (~2) for only two AGNs, NGC 2273 and NGC 3227. The PSF scaling results for these two AGNs were not consistent with the spectral decomposition. For this reason, we scaled the PSF to match the AGN contribution from the decomposition and used the results as upper limits. Figure 3 shows the results of the decomposition, high-resolution spectra from the GTC, and the total flux from SOFIA.

### Table 1. AGN properties

| Object   | Type | \( z \)  | Distance (Mpc) | Scale (pc/\( \prime \)) | \( \log L_{\text{bol}} \) (erg s\(^{-1}\)) | Ref.       |
|----------|------|----------|----------------|-------------------------|----------------------------------------|-----------|
| Mrk 3    | Sy2  | 0.0135   | 54.9           | 266                     | 45.1                                   | i,a       |
| NGC 1275 | RG/Sy1.5 | 0.0176 | 71.5           | 346                     | 44.8                                   | 2,ii,b    |
| NGC 2273 | Sy2  | 0.0061   | 25.0           | 121                     | 43.9                                   | 3,iii,c   |
| NGC 3081 | Sy2  | 0.0080   | 32.4           | 157                     | 44.2                                   | 4,iv,a    |
| NGC 3227 | Sy1.5| 0.0039   | 15.7           | 76                      | 43.3                                   | 5,v,a     |
| NGC 4151 | Sy1.5| 0.0033   | 13.0           | 63                      | 43.9                                   | 5,v,d     |
| NGC 4388 | Sy2  | 0.0047   | 19.0           | 92                      | 44.7                                   | 6,vi,a    |

**References:** Seyfert type: 1) Khachikian & Weedman (1974), 2) Alonso-Herrero et al. (2016), 3) Contini et al. (1998), 4) Phillips et al. (1983), 5) Véron-Cetty & Véron (2010), 6) Trippe et al. (2010). Redshift: i) Tiff & Coche (1988), ii) Strauss et al. (1992), iii) Ruiz et al. (2005), iv) Theureau et al. (2005), v) de Vaucouleurs et al. (1991) vi) Lu et al. (1995), vii) Tifft & Cocke (1988), viii) Strauss et al. (1992), ix) Ruiz et al. (2005), x) Theureau et al. (2005). Distances were calculated using \( H_0 = 73.8 \) km s\(^{-1}\)Mpc\(^{-1}\). Luminosities: a) Ichikawa et al. (2017) b)Baumgartner et al. (2013), c) Marinucci et al. (2012), d) Marconi et al. (2004)
Table 2. Observational data

| Object | Standard | PSF FWHMs | AGN FWHMs | Observing Date | t_on−source |
|--------|----------|-----------|------------|----------------|-------------|
|        |          | 31.5 µm  | 37.1 µm   | 31.5 µm        | 37.1 µm     | (yyyy-mm-dd) | (seconds) |
|        | (arcsec²) | (arcsec²) | (arcsec²) | (arcsec²) |          |             |           |
| Mrk 3  | β UMi    | 4.57 x 4.32 | 4.62 x 4.63 | 4.58 x 4.13 | 5.28 x 4.58 | 2016-09-27  | 288, 390  |
| NGC 1275 | γ Dra  | 4.05 x 3.68 | 4.61 x 4.34 | 3.85 x 4.31 | 4.87 x 4.55 | 2016-02-06  | 292, 397  |
| NGC 2273 | β And   | 4.13 x 3.77 | 4.56 x 4.28 | ...          | ...         | 2016-09-27  | 547, 700  |
| NGC 3081 | α Boo   | ...        | ...        | 4.70 x 4.81  | ...         | 2016-02-17  | 699       |
| NGC 3227 | Europa  | ...        | 4.47 x 4.19 | ...          | ...         | 2016-02-17  | 705       |
| NGC 4151 | α Boo   | ...        | 4.59 x 4.35 | ...          | ...         | 2016-02-17  | 369       |
| NGC 4388 | γ Dra   | ...        | 4.61 x 4.34 | ...          | ...         | 2016-02-06  | 378       |

Column 2: Name of the PSF standard star. Columns 3,4: Major and minor axes of the 31.5, 37.1 µm PSF FWHM. Columns 5,6: Major and minor axes of the 31.5, 37.1 µm AGN FWHM. Column 7: Date of observations. Column 8: On source time for the 31.5 and 37.1 µm filters. Some PSF standards are used for multiple science targets.

Figure 1. Radial profiles of the PSFs (solid black line) constructed as described in Section 2.3 compared to those of the AGNs (solid violet line). The regions shaded with horizontal bars indicate uncertainty from the background and from variations in the signal at increasing radii from the center. The top panel contains the 3 AGNs observed in both the 31.5 and 37.1 µm filters, whereas the bottom panel contains the 4 AGNs observed in only the 37.1 µm filter.

4 ORIGIN OF EXTENDED EMISSION

Our PSF-scaling results show residual extended galaxy emission at 37.1 µm for the six objects in our sample on which we performed the scaling. In this section we examine the origin of the extended residual emission, which would ostensibly originate from star forming regions, the NLR, or possibly even the torus or host galaxy. We use only the extended 37.1 µm emission since it is the common filter between each AGN in this sample.
Figure 2. SOFIA/FORCAST 31.5 and 37.1 µm filter images of AGN sample. Each mosaic is a 20” × 20” image centered on the position of peak emission. North is up, east is to the left. Top: Galaxies observed at both 31.5 and 37.1 µm. Bottom: Galaxies observed at only 37.1 µm. Lowest contours are 3σ and increase in steps of 5σ (contours of NGC 1275 increase in steps of 10σ).

Table 3. 31.5 and 37.1 µm flux densities

| Object | 31.5 µm | 37.1 µm |
|--------|---------|---------|
|        | F_{tot} (Jy) | PSF_{scale} (%) | F_{PSF} (Jy) | F_{tot} (Jy) | PSF_{scale} (%) | F_{PSF} (Jy) |
| Mrk 3  | 2.9 ± 0.3 | 70 | 1.8 ± 0.2 | 3.0 ± 0.3 | 70 | 1.9 ± 0.3 |
| NGC 1275 | 4.0 ± 0.5 | 80 | 3.0 ± 0.5 | 5.0 ± 0.8 | 70 | 3.2 ± 0.7 |
| NGC 2273 | 1.9 ± 0.2 | 55 | 1.0 ± 0.1 | 2.7 ± 0.3 | 50 | 1.2 ± 0.1 |
| NGC 3081 | 0.8 ± 0.1 | 100 | 0.8 ± 0.1 | 1.4 ± 0.2 | 100 | 1.4 ± 0.2 |
| NGC 3227 | ... | ... | ... | 2.8 ± 0.3 | 45 | 1.1 ± 0.1 |
| NGC 4151 | ... | ... | ... | 4.5 ± 0.6 | 70 | 2.7 ± 0.5 |
| NGC 4388 | ... | ... | ... | 3.2 ± 0.3 | 70 | 1.8 ± 0.3 |

Column 2: Total flux of the AGN observation; Column 3: % of the PSF scaling; Column 4: Flux of unresolved torus; Columns 5-7: same as columns 2-4 for 37.1 µm observations.

MIR emission is substantially less affected by extinction from the host galaxy than optical or UV observations. PAHs, which are indicative of stellar processes, emit strongly in MIR spectra (Roche et al. 1991b; Genzel et al. 1998; Förster Schreiber et al. 2004; Peeters et al. 2004), the most prominent and recognizable emission line features occurring at 3.3, 6.2, 7.7, 8.6, 11.3, 12.7, and 17.0 µm. PAHs absorb mostly UV photons (Uchida et al. 1998) and are associated with photon energies between 6 - 13.6 eV.

Genzel et al. (1998) show a direct correlation between AGN activity and the strength of high ionization lines such as [Ne v] 14.3, 24.3 µm and [O iv] 25.9 µm because of their high ionization potentials. [Ne v] 14.3, 24.3 µm, is commonly used to distinguish AGN related activity (Sturm et al. 2000; Abel & Satyapal 2008) from the NLR and not star formation.
and can affect the morphology of the NLR. Hence, \( \text{O}^{}(1998) \) found that radio jets interact with gas near the AGN. \HST\ optical observations to radio observations, Falcke et al. with the radio axis to within a few degrees. By comparing iii \( \text{O}^{}^{} \) sample showed extended MIR emission aligned with the the iv \( \text{O}^{}^{} \) emission and nuclear extension. Eighteen objects in their nomenclature 

\[
\begin{align*}
\text{NGC2273} & \quad \text{Spitzer} \\
& \quad \text{PAH+AGN} \\
& \quad \text{GTC} \\
& \quad \text{AGN} \\
& \quad \text{PAH} \\
& \quad F_{\text{tot}} \\
\end{align*}
\]

\[
\begin{align*}
\text{NGC3227} & \quad \text{Spitzer} \\
& \quad \text{PAH+AGN} \\
& \quad \text{GTC} \\
& \quad \text{AGN} \\
& \quad \text{PAH} \\
& \quad F_{\text{tot}} \\
\end{align*}
\]

Figure 3. A spectral decomposition with a reduced \( \chi^2 \) was only available for two objects: NGC 2273 and NGC 3227. Results of the decomposition using DeblendIRS (Hernán-Caballero et al. 2015) are shown here. Spectra are separated into a PAH component (green) and the AGN component (red). The sum of the two components is shown here in light blue, which coincides with the original Spitzer spectra in black. The AGN component coincides with with sub-arcsecond GTC spectra (dark blue), while the total flux from SOFIA coincides with the Spitzer continuum.

since the production of \( \text{Ne}^{4+} \) requires photons with energies greater than \( \sim 97 \text{ eV} \). Likewise, \([\text{O} \ IV]\) 25.9 \( \mu \text{m}\) is an effective tracer of AGN activity (Meléndez et al. 2008; Rigby et al. 2009; Diamond-Stanic et al. 2009) with an ionization potential of \( \sim 55 \text{ eV} \).

Asmus et al. (2016) use \([\text{O} \ IV]\) 25.9 \( \mu \text{m}\) as a tracer of NLR activity and find a direct correlation between strong \([\text{O} \ IV]\) emission and nuclear extension. Eighteen objects in their sample showed extended MIR emission aligned with the the \([\text{O} \ III]\) 5.5007 and radio axes. Haniff et al. (1988) found that, in a sample of 10 Seyfert galaxies, \([\text{O} \ III]\) emission is aligned with the radio axis to within a few degrees. By comparing \HST\ optical observations to radio observations, Falcke et al. (1998) found that radio jets interact with gas near the AGN and can affect the morphology of the NLR. Hence, \([\text{O} \ IV]\) can probe the NLR, which should be aligned with the optical and radio axes.

In the following subsections, we use the 37.1 \( \mu \text{m}\) residual images from the PSF-scaling as well as redshift-corrected 5 - 38 \( \mu \text{m}\) spectra from the \textit{Spitzer} CASSIS library (Lebouteiller et al. 2011) to determine the origin of extended emission on arcsecond scales. We compare the residual image with optical observations, which were smoothed to reduce background noise, as well as the radio axis P.A. We use PAH features at 6.2, 7.7, 8.6, and 11.3 \( \mu \text{m}\) as diagnostics for star formation, but do not use the 12.7 or 17.0 \( \mu \text{m}\) lines due to blending with \( \text{H}_2 \) and \([\text{Ne} \ II]\) 12.8 \( \mu \text{m}\). We also compare the arcsecond-scale spectra from \textit{Spitzer} to subarcsecond N-band spectra (Table 4) and determine the amount of extended 12 \( \mu \text{m}\) emission. This wavelength was chosen because it is not heavily affected by 9.7 \( \mu \text{m}\) silicate absorption and also avoids the main 11.3 and 12.7 \( \mu \text{m}\) PAH features, though the amount of extended emission is highly variable in this wavelength range.

### 4.1 Mrk 3

The top left panel of Figure 4 shows the SOFIA 37.1 \( \mu \text{m}\) residual image of Mrk 3 with contours in black overlaid by optical \([\text{O} \ III]\) 5.5007 (Capetti et al. 1995) contours in white. Both wavelengths show clear elongation toward the east/west direction, suggesting a common origin. Capetti et al. (1996) associated this optical emission with the NLR and showed a close association between NLR emission morphology and radio emission. A large-scale radio jet system extending 2\( ^{\circ} \) was also seen using MERLIN (Kukula et al. 1993) with a P.A. along 84\( ^{\circ} \). The radio axis is shown in green at a scale of 500 pc, in close alignment with the NLR.

[Table 4. Sub-arcsecond spectroscopy]

| Object   | Instrument          | Slit Width (") | Ref. |
|----------|---------------------|----------------|------|
| Mrk 3    | GTC/CanariCam       | 0.52           | a    |
| NGC 1275 | GTC/CanariCam       | 0.52           | a    |
| NGC 2273 | GTC/CanariCam       | 0.52           | a    |
| NGC 3081 | Gemini/T-ReCS       | 0.65           | b    |
| NGC 3227 | GTC/CanariCam       | 0.52           | a    |
| NGC 4151 | Gemini/Michelle     | 0.36           | c    |
| NGC 4588 | GTC/CanariCam       | 0.52           | a    |

References: a) Alonso-Herrero et al. (2016), b) González-Martín et al. (2013), c) Alonso-Herrero et al. (2011)
30 - 40 μm AGN Observations on SOFIA

Figure 4. Left: 37.1 μm residual images of Mrk 3, NGC 1275, and NGC 2273 with 3σ contour (black) and HST optical contours overlaid in white. The peak MIR image is centered and aligned with the peak of the optical image. The radio axis is highlighted in green at a scale of 500 pc. In all images, North is up and East is to the left. Right: Spitzer spectra (black solid line) compared to sub-arcsecond N-band spectra (solid blue line). The Spitzer spectrum is also compared to the total image flux from obtained from our data (star), while the PSF-scaled flux is also shown (solid black dot). PAH features, if present, are highlighted in red.

4.2 NGC 1275

NGC 1275 is an atypical elliptical Seyfert galaxy displaying a network of Hα filaments and is possibly the result of a merger (Holtzman et al. 1992). The 37.1 μm residual image, shown on the middle left panel of Figure 4, shows some tentative extension, possibly indicating a contribution from outflows in the galaxy (Conselice et al. 2001). The white contours, corresponding to optical continuum emission (Carlson et al. 1998), clearly show strong, point-like emission from the nucleus, but does not show any similar extension. The radio axis is shown in green at a PA of 160° (Asmus et al. 2016).

The Spitzer spectrum in the middle right panel of Fig-
ure 4 shows almost no MIR features. The 12 μm emission determined by the N-band GTC spectrum comprises 83% of the total dust emission as seen by Spitzer, suggesting that the 10 μm silicate emission feature seen in the Spitzer spectrum originates from the same subarcsecond-scale source. For NGC 1275, this corresponds spatially to a source <~140 pc. Due to the lack of spectral lines and insufficient correspondence between wavelength axes, the data do not allow us to conclude the origin of residual emission.

### 4.3 NGC 2273

NGC 2273 is known to harbor a star forming ring within ~2” from the AGN (Ferruit et al. 2000; Martini et al. 2003; Sani et al. 2012). In the bottom left panel of Figure 4, nuclear optical [O iii] λ5007 emission (Ferruit et al. 2000) is compared with the 37.1 μm residuals from SOFIA. GTC observations by Alonso-Herrero et al. (2014) at 8.7 μm reveal extension to the northeast and southwest, coincident with the [O iii] extension in Figure 4. The SOFIA residual is consistent with the elongation of the [O iii] extensions to the southwest. The extension is not aligned with the radio axis, PA ~ 95° (Nagar et al. 1999), highlighted in green.

The Spitzer spectrum in the bottom right panel of Figure 4 shows strong PAH emission features and weak [O iv] 25.9 μm emission. We conclude that the residual emission is most likely due to star formation in NGC 2273 because 1) the residual emission is approximately aligned with star forming regions, 2) there is no correlation between the radio axis and residual image, and 3) strong PAH features are seen in the Spitzer spectrum. At 12 μm, subarcsecond emission accounts for ~63% of the emission measured by Spitzer, suggesting that star formation occurs on scales ~ 0.3 - 3” (~35 - 450 pc), within the FWHM of SOFIA.

### 4.4 NGC 3081

The left panel of Figure 5 shows the SOFIA image of NGC 3081; the image is not included in Figure 4 because we did not perform a PSF subtraction and, hence, do not have a residual image. On larger scales, this galaxy is notable for its series of kpc-scale diameter ringed structures: a nuclear ring (D = 2.3 kpc), an inner ring (D =11.0 kpc), an outer ring (D = 26.9 kpc), and a “pseudo-ring” (D = 31.1 kpc) (Buts 1990; Buts & Pursell 1998; Buts et al. 2004; Byrd et al. 2006). The nuclear ring has a PA of ~120° and a major axis of ~ 12” (Ferruit et al. 2000). On smaller scales, [O iii] λ5007 observations clearly show a bright region of optical emission ~1” north of the nucleus (Ferruit et al. 2000). The [O iii]/([N ii]+Hα) ratio of the bright emission is similar to that of the nucleus suggesting that the bright region is related to dust or gas heated by the AGN and that stellar processes are not responsible for photoionization in that region. Ramos Almeida et al. (2011) presented Herschel imaging data from 70 to 500 μm, where they fitted the NIF to FIR SED and concluded that on scales ≤0.85 kpc, the FIR nuclear luminosity was reproduced by cool dust in the torus heated by the AGN.

Nagar et al. (1999) observed a radio axis ~160° without a prominent radio jet. Neither the optical nor radio axes are consistent with the east-west extension seen in the SOFIA 37.1 μm image, giving an unclear explanation to its origin. This inconsistency further compelled the use of total flux from the PSF scaling as an upper limit, as mentioned in Section 3.

The Spitzer spectrum in Figure 5 shows very weak PAH emission, but does show very strong [O iv] 25.9 μm emission line, as well as [Ne v] 24.3 μm emission line, suggesting NLR activity. At 12 μm, subarcsecond emission as determined by Gemini/T-ReCS accounts for ~65% of emission from Spitzer, signaling that any extended emission occurs on scales ~50 - 600 pc. The Spitzer continuum is consistent with the total SOFIA emission at 37.1 μm, however it is not consistent with the 31.5 μm total flux.

### 4.5 NGC 3227

NGC 3227 is another galaxy known for circumnuclear star formation (Schinnerer et al. 2001; Rodríguez-Ardila & Viegas 2003; Davies et al. 2006). The top left panel of Figure 6 shows the 37.1 μm residual emission, as well as optical emission (Malkan et al. 1998) using the F606W HST filter. Mundell et al. (1995) found that the optical [O iii] λ5007 axis has a P.A. ~ 30° extending ~ 500 pc (~6.5”) to the NE that is aligned with the NLR, but does not coincide with the radio axis (PA ~ -10°). We do not find a similar extension in the SOFIA observations. However, Schmitt & Kinney (1996) found using HST observations that the [O iii] λ5007 emission extends to the NE with P.A. ~ 15° at a distance of 100 pc (1.4”), thus within the FWHM of our SOFIA observations.

The Spitzer spectrum on the top right panel of Figure 6 shows prominent PAH features. Comparing that to the subarcsecond GTC spectrum, which shows no PAH features, suggests that most star forming activity occurs between 0.3 - 3 arcseconds (~20 - 270 pc), similar to the comparison of VISIR to Spitzer by Höning et al. (2010); Jensen et al. (2017). Schinnerer et al. (2001) found a nuclear stellar cluster within ~70 pc of the core. The 12 μm emission estimated from the GTC spectrum accounts for ~60% of arcsecond-scale emission as determined by Spitzer. The spectrum also shows that the [O iv] 25.9 μm line, while not as prominent as in other AGN in this sample, is still clearly detected. While the [O iv] feature would suggest activity in the NLR, strong PAH in the spectrum suggests that the source of residual emission is primarily stellar heating. Both emission sources should be considered when modeling the mid- to far-IR emission of this AGN.

### 4.6 NGC 4151

NGC 4151 is a nearby, well-studied Seyfert 1.5 galaxy. The residual image is shown in the middle left panel of Figure 6 with optical contours (Kaiser et al. 2000) overlaid in white. Using MIR observations from Gemini, Radomski et al. (2003) showed extended emission at 10.8 and 18.2 μm in the central 3.5” at a P.A. of ~60°. They demonstrated that the MIR extension coincides with the NLR, as determined by [O ii] λλ5007 observations (Evans et al. 1993; Kaiser et al. 2000). Additionally, Radomski et al. (2003) very thoroughly isolated the extended emission as NLR dust based on grain size and composition. While the comparison
between SOFIA residuals and HST contours in Figure 6 are not quite on the same scale, the general P.A. \( \sim 70^\circ \) of the [O iii] \( \lambda 5007 \) emission (Asmus et al. 2016) is roughly consistent with the extension in the SOFIA residual, and is similar to the radio axis P.A. \( \sim 77^\circ \) (Pedlar et al. 1998), shown in green at a scale of 500 pc.

The Spitzer spectrum in the middle right panel of Figure 6 shows [O iv] and [Ne v] emission lines, with minimal PAH, indicative of little or no major star formation. Comparison of subarcsecond-scale emission at 12 \( \mu m \) shows that nuclear emission accounts for \( \sim 70\% \) of emission determined by Spitzer, suggesting that extended emission occurs between \( \sim 20 - 225 \) pc. The consistency of the P.A. of the 37.1 \( \mu m \) image with optical line emission, as well as arcsecond-scale spectral features, strongly suggests that the source of extended emission in NGC 4151 is the NLR.

### 4.7 NGC 4388

The 37.1 \( \mu m \) residual image of NGC 4388 in the bottom left panel of Figure 6 clearly shows extension to the northeast and southwest at P.A. \( \sim 40^\circ \), in the same direction as well-known galactic outflows (Veilleux et al. 1999; Rodríguez-Ardila et al. 2017). The optical [O iii] \( \lambda 5007 \) white contours (Falcke et al. 1998) show a well-defined ionization cone to the southeast. The northeast extension, clearly visible in the residual image, is likely extinguished in the optical image by the host galaxy, which has a P.A. of 91°. The good alignment between the optical and radio morphologies (P.A. 30°) suggests that the radio jet in NGC 4388 interacts with gas in the NLR (Falcke et al. 1998). NIR spectroscopic observations of Rodríguez-Ardila et al. (2017) show that photoionization by radiation from the central engine does not account for all photoionization observed in the ionization cone and suggest that dust interaction with the radio jet must occur in the central few hundred parsecs of the nucleus.

The Spitzer spectrum in the bottom right panel of Figure 6 shows some PAH emission, though it is possible that the 7.7 \( \mu m \) feature is blended with [Ne vi] 7.6 \( \mu m \). The [O iv] 25.9 \( \mu m \) line is prominent and is neighbored by a visible [Ne v] fine structure line. Subarcsecond-scale 12 \( \mu m \) emission as determined by the GTC spectrum accounts for \( \sim 88\% \) of 12 \( \mu m \) Spitzer emission, suggesting a common source found spatially \( \lesssim 40 \) pc. However, the PSF scaling suggests that this percentage decreases at longer wavelengths. Even though this spectrum shows some star forming activity, the distinct alignment of the residual image to the optical and radio axes suggests that the extended 37.1 \( \mu m \) emission is primarily from the NLR, while star formation may have some minor contribution.

### 4.8 Extended NLR Emission

Figures 4 and 6 of Mrk 3 and NGC 4388 clearly show extended emission in the direction of the NLR and radio axes, as well as spectra that are consistent with NLR emission. The spectrum of NGC 4151 is also consistent with NLR emission, but the residual image axis is not quite as clear. This could be because Mrk 3 and NGC 4388 are both Sy2 AGN and seen edge-on, whereas NGC 4151 is a Sy1.5. According to Fischer et al. (2013), the inclination angle of the NLR bicone of Mrk 3 is 5° whereas the inclination of the NLR bicone of NGC 4151 is 45°, indicating that clear elongation would not be seen in the residual image of NGC 4151.

Table 5 shows that the residual fluxes for the given AGNs in our sample increase from 31.5 to 37.1 \( \mu m \) (NGC 3081 and NGC 4151 are not included due to lack of data). From the residual fluxes, a tentative estimate of the temperature for the emitting regions can be made by modeling the emission as a single temperature blackbody. Temperatures which fit within their error bars. The uncertainty in the measurement would be greatly improved with more data points.

Using these tentative dust temperatures, the dust mass can be estimated by the relation:

\[
F_V = \kappa_V B_V(T)M_D D_L^2
\]
Figure 6. Left: 37.1 μm residual images with 3σ contours (black) with optical contours overlaid in white. The peak of the MIR image is centered and aligned with the peak of the optical image. The radio axis is highlighted in green at a scale of 500 pc. In all images, North is up and East is to the left. Right: Spitzer spectra (black solid line) compared to sub-arcsecond 8 - 13 μm spectra (solid blue line). The red dashed vertical lines highlight the strength of PAH features. The Spitzer spectra are also compared to the total image flux obtained from our data (star), while the PSF-scaled flux is also shown (solid black dot).
Table 5. 31.5 and 37.1 µm residual fluxes

| Object   | 31.5 µm Res. Flux (Jy) | 37.1 µm Res. Flux (Jy) | Estimated Temp. (K) | Dust Mass (M⊙) |
|----------|------------------------|------------------------|---------------------|----------------|
| Mrk 3    | 11.1 ± 4               | 12.1 ± 5               | 78 ± 11             | 1.1 ± 10        |
| NGC 1275 | 1.0 ± 7                | 1.6 ± 7                | 51 ± 4              | 4.0 ± 10        |
| NGC 2273 | 0.8 ± 2                | 1.5 ± 4                | 51 ± 4              | 4.9 ± 10        |
| NGC 3081 |                        |                        |                     |                |
| NGC 3277 | 1.1 ± 3                | 1.7 ± 4                | 59 ± 1             | 6.4 ± 10        |
| NGC 4511 |                        | 1.8 ± 4                | 70 ± 1             | 2.3 ± 10        |
| NGC 4388 | 1.2 ± 5                | 1.4 ± 4                | 70 ± 1             | 2.3 ± 10        |

(1) Gratadour et al. (2006) simplified the calculation of Barvainis (1987) to describe the temperature, $T$, of dust grains at a distance, $r$, from the nucleus given a UV luminosity, $L_{uv}$,:

$$T = 1650 \times \left( \frac{L_{uv}}{r^2} \right)^{\frac{1}{4}} K$$

in order to put an upper limit on the temperature caused by AGN heating. Here, we use the blackbody temperatures in Table 5 to estimate the distance at which dust can be heated by the central excitation source. Kishimoto et al. (2002) find an upper limit for the UV luminosity of Mrk 3 as $\sim 3 \times 10^{44}$ erg s$^{-1}$, resulting in a radial distance of $r \sim 900$ pc. The extent of the NLR for Mrk 3 according to Figure 4 is about 4′, which corresponds to $\sim 1$ kpc in the SOFIA image. Collina (1992) report a UV luminosity of 1.7 × 10$^{43}$ erg s$^{-1}$ for NGC 4388, suggesting that dust can be heated to a distance $\sim 300$ pc. The extended emission shown in Figure 6 reaches $\sim 350$ pc. While the relation underestimates the radial extent that the central excitation source given the estimated temperatures, we show here that the extended emission seen in the residual images is consistent with spatial scales at which dust can be heated by the central engine (0.1 - 1 kpc). These physical scales are consistent with other studies (Groves et al. 2006; Schweitzer et al. 2008; Mor et al. 2009; Mor & Netzer 2012). More data regarding the dust temperature is needed to refine this analysis.

4.9 MIR Spitzer Continuum

Deo et al. (2009) showed that Seyfert 2 AGN can be separated into two groups - those that show strong PAH in their Spitzer spectra, and those that are AGN-dominated and show little to no PAH. Those that are AGN-dominated have much flatter continua between 20 - 30 µm. Likewise, we find that Mrk 3 and NGC 4151 have very weak traces of PAH in their spectra, strong [O iv] emission, and also have the flattest 20 - 30 µm continua in our sample. These two AGN also show collimation along the system axis in the 37.1 µm residual image. This suggests that AGN with flat 20 - 30 µm Spitzer continua would likely contain an NLR component in their MIR SED.

5 NUCLEAR SED MODELING

In order to analyze the nuclear IR SED of the unresolved torus, we compiled the highest angular resolution NIR and MIR data available from the literature, for the 7 AGN in our sample. Subarcsecond-resolution NIR fluxes are available for 6 galaxies using NICMOS/HST and IRCam3/UKIRT. Mrk 3 is an exception, wherein we use NIR flux data from WISE (Ichikawa et al. 2017) as an upper limit. Subarcsecond-resolution MIR photometry was obtained for 6 galaxies using Gemini North/South, Subaru, and VLT; MIR $\nu$ and $Q$ band photometry for NGC 2273 was not available. N-band observations probe the central $\sim 0.3′$ - 0.6′, which corresponds to $\sim 20 - 35$ pc for NGC 2273, NGC 3227, NGC 4151, and NGC 4388. However, for Mrk 3, NGC 1275, and NGC 3081, this resolution probes scales $\sim 90 - 140$ pc. For all objects at all wavelengths, non-torus contaminating emission was estimated and removed in their respective analyses by the authors of the papers cited in Table 6.

In the previous section we showed that some extended emission from SOFIA observations is due to a component that we suggest is dust in the NLR. An accurate estimation of the level of contribution to the total SED is highly model dependent, but we note that when modeling mid- to far-IR emission, both star formation and the additional component should be taken into consideration. For this reason, and because of the inability to perform a spectral decomposition as explained in Section 3, we use the PSF-subtracted photometric data from SOFIA as an upper limit to model the 1 - 40 µm SED of the unresolved torus.

The CLUMPY torus models of Nenkova et al. (2008a) assert that dust around the central engine of an AGN is distributed in clumps that can be primarily described by six physical properties: a radial distribution power law index $q$ ($\propto r^{-q}$); the torus opening angle width $\sigma$; the torus inclination angle $i$; total number of clouds in some line of sight $N_0$; an optical depth per cloud, $\tau_c$; and the outer to inner radial ratio $R = R_{out}/R_{in}$, where $R_{in}$ is set set by the dust sublimation temperature, $T_{sub}$, $\sim 1500$K, and computed by bolometric luminosity $L_{bol} = 0.4(L_{bol}/10^{45})^{0.5}$ pc (Barvainis 1987).

Using the Bayesian inference tool BAYESCLUMPY (Asensio Ramos & Ramos Almeida 2009), we fit the IR SED using photometry in Table 6 and spectroscopy in Table 4 as inputs to infer physical properties of the torus. This tool uses the photometric and spectroscopic inputs to detect all possible combinations of model parameters consistent with...
the observations, and outputs probability distributions of the parameters. We used the highest resolution photometric and spectroscopic data available to construct the 1-20 𝜇m SEDs, then added SOFIA data from F16 and this work. The spectra have been resampled to ~ 50 data points, following the methodology of Alonso-Herrero et al. (2013; Ramos Almeida et al. (2014).

The output model SEDs are shown in Figure 7. The blue lines mark the output SEDs computed with the median values while the blue shaded regions indicate 1σ uncertainty. Photometric and spectroscopic inputs are shown in black. The SED results suggest that we may have observationally begun to determine a range of wavelengths where peak emission from the torus occurs, though the difference in flux densities is within error (see Table 3). Likewise, Lopez-Rodriguez et al. (2018) find a similar peak wavelength of MIR emission for NGC 1068 between 30 - 40 𝜇m.

Even though the 31.5 and 37.1 𝜇m photometry is given as an upper limit, the model overestimates torus emission in NGC 3227 and NGC 4388. F16 show that the model SEDs tend to significantly overestimate torus emission in the absence of 31.5 𝜇m data. The overestimation of the SED in Figure 7 may suggest that a simple clumpy dust model may not fully describe torus emission, and perhaps a two-phase medium (e.g. Siebenmorgen et al. 2015) should be explored in more detail. Figure 7 shows a poor NIR fitting to NGC 4388, and the 8 - 13 𝜇m spectrum also shows a deep silicate absorption feature. It is possible that a dusty NLR contaminates the NIR data and increases the amount of silicate absorption.

The posterior numerical outputs are given in Table 7 and the distributions are shown in Figure 8. The average posterior outputs for NGC 3227, NGC 4151, and NGC 4388 tend to have narrow distributions. For example, the average uncertainty in the outputs (excluding the error in 𝜙) for these AGNs is ±3, while the average uncertainty in the outputs of the remaining four AGNs in the sample is ±6. These three AGNs also show a tentative turnover in torus emission between 30 - 40 𝜇m, suggesting that sampling with these longer wavelengths produces more precise determinations of torus parameters. However, a larger sample is needed in order to confirm this correlation.

Using the relation \( R_{\text{torus}} = Y R_{\odot} \), the \( Y \) parameter yields torus outer radii ~ 1 - 6 pc, consistent with observations (Jaffe et al. 2004; Packham et al. 2005; Tristram et al. 2007; Radomski et al. 2008; García-Burillo et al. 2016), and the estimates of previous clumpy torus model SED fittings (e.g. Ramos Almeida et al. 2009, 2011; Alonso-Herrero et al. 2011; Ichikawa et al. 2015).

5.1 Constraint of Extended Emission Source in FIR

The contribution of dust emission at wavelengths > 30 𝜇m is often attributed solely to star formation. To explore the possible components contributing to FIR emission, we use available Herschel data for NGC 4151 (Siebenmorgen et al. 2015; García-González et al. 2016) and compare it to a predicted FIR contribution from the NLR as well as star formation. Using the torus SED output from BAYESCLUMPY, we combine torus SED with 1) a scaled starburst template, and 2) a 75 K blackbody representative of continuum NLR emission (see temperature discussion in Section 4.8). The starburst template (Mullaney et al. 2011) uses Spitzer/IRS spectra of an averaged subset of starburst nuclei (Brandl et al. 2006), then extrapolates FIR emission out to 100 𝜇m using IRAS photometry. The starburst template and blackbody are scaled to the residual 37.1 𝜇m flux of NGC 4151, which we use here as a lower limit. The total FIR emission is then compared to Herschel 70 and 100 𝜇m fluxes (Siebenmorgen et al. 2015), using the Herschel fluxes as upper limits. García-González et al. (2016) used Herschel data to identify nearby AGNs with 70 𝜇m emission dominated by dust heated by the AGN and estimated a range of the AGN flux at 70 𝜇m. They estimated that 49 - 60% of the flux in NGC 4151 within 1 kpc is due to dust heated by the AGN (both torus and NLR). That equates to a 70 𝜇m flux due to dust heated by the AGN at approximately 2.4 - 3.0 Jy.

The top panel of Figure 9 shows the total FIR emission when adding the starburst template SB3 (orange dotted line) to the torus SED (solid black line). The stellar template SB3, which represents host-galaxy emission, was selected because of its relatively shallow FIR slope compared to other starburst templates. The total emission using the Torus + SB3 (green dashed line) exceeds the 100 𝜇m upper limit set by Herschel, as well as the predicted AGN contribution range of García-González et al. (2016) (shown in pink). The bottom panel of Figure 9 shows total FIR emission when combining the 75 K blackbody (red dotted line) with the torus SED (solid black line). The total emission of the system, Torus + 75K (blue dashed line), fits well within the upper limits set by Herschel and better represents FIR emission. The total emission also does not exceed the predicted AGN emission within 1 kpc.

In NGC 4151, FIR emission likely has some contribution from star formation or host galaxy which fit well within the Herschel upper limits. Assuming a single source of emission in the residuals is likely not physically accurate. In fact, a variety of blackbody and star formation template scaling can describe the upper limit FIR emission out to 100 𝜇m. However, more data is needed to accurately describe the full FIR SED.

6 SUMMARY AND CONCLUSIONS

We have presented new 37.1 𝜇m imaging observations from the SOFIA telescope for 7 AGNs. Of these 7, 3 were also observed using the 31.5 𝜇m filter. To estimate torus emission within the aperture of SOFIA, we used the PSF-scaling method described by F16. Three of the 1 - 40 𝜇m SEDs tentatively show a turnover in torus emission, suggesting that observations in the 30 - 40 𝜇m range are needed to find peak torus emission.

We examined the origin of extended emission and show, for the first time, extended 37.1 𝜇m emission in Mrk 3, NGC 4151, and NGC 4388 that is consistent with the NLR and radio axes. Spectra from the Spitzer CASSIS database (Lebouteiller et al. 2011) generally show either strong PAH

\footnote{https://sites.google.com/site/decompir/}
features, which is attributed to star forming regions, or a strong \([\text{O} IV]\) 25.9 \(\mu m\) fine structure line, suggesting emission from the NLR. We find that extended emission within the 3 - 4'' FWHM of SOFIA can generally be attributed to either star formation or some elongated component consistent with the NLR.

The elongated NLR component in our observations suggests that dust can be heated by the AGN on scales of hundreds of parsecs. In order to demonstrate this viability, we constructed the NLR heated by the AGN. We find that scaling the starburst template to the residual emission overestimates FIR emission, while scaling the blackbody representing the NLR continuum fits a more accurate description.

ACKNOWLEDGEMENTS

Based on observations made with the NASA/DLR Stratospheric Observatory For Infrared Astronomy (SOFIA). SOFIA is jointly operated by the Universities Space Research Association, Inc. (USRA), under NASA contract NAS2-97001, and the Deutsches SOFIA Institut (DSI) under DLR contract 50 OK 0901 to the University of Stuttgart. Financial support for this work was provided by NASA through award #02-0035, #04-0048, and #06-0066 issued by USRA. L.F. and C.P. acknowledge support from the NSF-DLR contract 50 OK 0901 to the University of Stuttgart. T.D.-S. acknowledges support from the NSF-DLR contract 50 OK 0901 to the University of Stuttgart. We thank the NASA/DLR Stratospheric Observatory For Infrared Astronomy (SOFIA) for making these observations possible. SOFIA is jointly operated by the Universities Space Research Association, Inc. (USRA), under NASA contract NAS2-97001, and the Deutsches SOFIA Institut (DSI) under DLR contract 50 OK 0901 to the University of Stuttgart. Financial support for this work was provided by NASA through award #02-0035, #04-0048, and #06-0066 issued by USRA. L.F. and C.P. acknowledge support from the NSF-DLR contract 50 OK 0901 to the University of Stuttgart.

REFERENCES

Abel N. P., Satyapal S., 2008, ApJ, 678, 686
Alonso-Herrero A., Ward M. J., Kotilainen J. K., 1997, MNRAS, 288, 977
Alonso-Herrero A., Quillen A. C., Rieke G. H., Ivanov V. D., Efstathiou A., 2005, AJ, 129, 81
Alonso-Herrero A., et al., 2011, ApJ, 736, 82
Alonso-Herrero A., et al., 2013, ApJ, 779, L14
Alonso-Herrero A., et al., 2014, MNRAS, 443, 2766

\[ \text{Table 6. High spatial resolution NIR and MIR flux data} \]

| Object   | \( J \)  | \( H \)  | \( K \)  | \( L \)  | \( M \)  | \( N \)  | \( Q \)  | Ref(s) |
|----------|---------|---------|---------|---------|---------|---------|---------|--------|
| Mrk 3    | ...     | ...     | ...     | <0.06   | <0.076  | 448 ± 120| a,b     |
| NGC 1275 | ...     | 4.3 ± 0.4| ...     | ...     | ...     | 886 ± 11 | ...     |
| NGC 2273 | ...     | 0.32 ± 0.28| ...     | ...     | ...     | ...     | ...     |
| NGC 3081 | ...     | 0.22 ± 0.13| ...     | ...     | ...     | 83 ± 12  | 231 ± 58 | c,d     |
| NGC 3227 | ...     | 7.8 ± 0.8 | 16.6 ± 1.7| 46.7 ± 9.3| 72 ± 27 | 180 ± 11 | 772 ± 47 | e,f,g,h,b|
| NGC 4151 | 60 ± 3  | 100 ± 5  | 197 ± 10| 325 ± 65| 449 ± 34| 1320 ± 198| 3200 ± 800| e,g,d   |
| NGC 4388 | 0.06 ± 0.02 | 0.71 ± 0.28| ...     | 40 ± 8   | ...     | 195 ± 29 | 803 ± 201| f,d     |

\[ \text{Table 7. BayesClumpy output model parameters} \]

| Object   | \( \sigma \) | \( Y \) | \( N_{\text{dust}} \) | \( q \) | \( \tau_0 \) | \( t \) | \( R_{\text{m}} \) (\( \mu m \)) |
|----------|-----------|-------|----------------|------|--------|-----|----------|
| Mrk 3    | 57\pm 3   | 11\pm 1 | 14\pm 1 | 0.54\pm 0.15| 39\pm 2 | 81\pm 3 | 5.2 \pm 0.3 |
| NGC 1275 | 26\pm 2   | 10\pm 1 | 13\pm 1 | 1.17\pm 0.06| 144\pm 2 | 75\pm 3 | 3.1 \pm 0.3 |
| NGC 2273 | 62\pm 4   | 15\pm 1 | 13\pm 1 | 1.91\pm 0.29| 78\pm 4 | 78\pm 1 | 1.7 \pm 0.3 |
| NGC 3081 | 62\pm 4   | 12\pm 1 | 12\pm 1 | 2.48\pm 0.33| 106\pm 4 | 59\pm 3 | 1.8 \pm 0.3 |
| NGC 3227 | 56\pm 3   | 19\pm 1 | 13\pm 1 | 0.07\pm 0.02| 149\pm 2 | 10\pm 5 | 1.0 \pm 0.1 |
| NGC 4151 | 15\pm 1   | 26\pm 1 | 10\pm 1 | 1.56\pm 0.12| 131\pm 10| 70\pm 1 | 2.2 \pm 0.2 |
| NGC 4388 | 68\pm 2   | 23\pm 1 | 15\pm 1 | 0.60\pm 0.20| 31\pm 1 | 85\pm 4 | 6.4 \pm 0.4 |

- Mrk 3
- NGC 1275
- NGC 2273
- NGC 3081
- NGC 3227
- NGC 4151
- NGC 4388

\[ \text{References: a) Ichikawa et al. (2017) b) Asmus et al. (2014), c) Quillen et al. (2001), d) Ramos Almeida et al. (2009), e) Kishimoto et al. (2007), f) Alonso-Herrero et al. (2003), g) Ward et al. (1987), h) Hönig et al. (2010). Notes: The } N \text{ band photometry for NGC 3227 was taken in three different filters: 8.99, 11.88, and 11.29 \(\mu m\) using VLT and Gemini.} \]
Figure 7. BAYESCLUDY torus model fits. The blue line indicates the output SED computed with the median value of the probability distribution of each parameter. The blue shaded region indicates the range of models compatible with a 68% confidence level around the median. The output SEDs are shown with photometric (black dots) and 8 - 13 \textmu m spectroscopic (black line) inputs.

Alonso-Herrero A., et al., 2016, MNRAS, 455, 563
Antonucci R., 1993, ARA&A, 31, 473
Asensio Ramos A., Ramos Almeida C., 2009, ApJ, 696, 2075
Asensio Ramos A., Ramos Almeida C., 2013, MNRAS, 428, 195
Asmus D., Hönig S. F., Gandhi P., Smette A., Duschl W. J., 2014, MNRAS, 439, 1648
Asmus D., Hönig S. F., Gandhi P., 2016, ApJ, 822, 109
Barvainis R., 1987, ApJ, 320, 537
Baumgarten W. H., Tiedler J., Markwardt C. B., Skinner G. K., Barthelmy S., Mushotzky R. F., Evans P. A., Gehrels N., 2013, ApJS, 207, 19
Bernard-Salas J., et al., 2009, ApJS, 184, 230
Brandl B. R., et al., 2006, ApJ, 653, 1120
Buchanan C. L., Gallimore J. F., O’Dea C. P., Baum S. A., Axon D. J., Robinson A., Elitzur M., Elvis M., 2006, AJ, 132, 401
Burtscher L., et al., 2013, A&A, 558, A149
Buta R., 1990, ApJ, 351, 62
Buta R., Purcell G. B., 1998, AJ, 115, 484
Buta R. J., Byrd G. G., Freeman T., 2004, AJ, 127, 1982
Byrd G. G., Freeman T., Buta R. J., 2006, AJ, 131, 1377
Capetti A., Macchetto F., Axon D. J., Sparks W. B., Boksenberg A., 1995, ApJ, 448, 600
Capetti A., Axon D. J., Macchetto F., Sparks W. B., Boksenberg A., 1996, ApJ, 469, 554
Carlson M. N., et al., 1998, AJ, 115, 1778
Casey C. M., 2012, MNRAS, 425, 3094
Clavel J., et al., 2000, A&A, 357, 839
Colina L., 1992, ApJ, 386, 59
Conselice C. J., Gallagher III J. S., Wyse R. F. G., 2001, AJ, 122, 2281
Contini T., Considere S., Davoust E., 1998, A&A, 330, 285
Davies R. I., et al., 2006, ApJ, 646, 754
Deo R. P., Richards G. T., Crenshaw D. M., Kraemer S. B., 2009, ApJ, 705, 14
Diamond-Stanic A. M., Rieke G. H., Rigby J. R., 2009, ApJ, 698, 623
Dutson K. L., Edge A. C., Hinton J. A., Hogan M. T., Gurwell M. A., Alston W. N., 2014, MNRAS, 442, 2048
Esquej P., et al., 2014, ApJ, 780, 86
Evans I. N., Tsvetanov Z., Kriss G. A., Ford H. C., Caganoff S., Koratkar A. P., 1993, ApJ, 417, 82
Falcke H., Wilson A. S., Simpson C., 1998, ApJ, 502, 199
Ferruit P., Wilson A. S., Mulchaey J., 2000, ApJS, 128, 139
Fischer T. C., Crenshaw D. M., Kraemer S. B., Schmitt H. R., 2013, ApJS, 209, 1
Fürster Schreiber N. M., Rousset H., Sauvage M., Charmandaris V., 2004, A&A, 419, 501
Fuller L., et al., 2016, MNRAS, 462, 2618
García-Bernete I., et al., 2015, MNRAS, 449, 1309
García-Burillo S., et al., 2014, A&A, 567, A125

MNRAS 000, 1–17 (2018)
## Figure 8. BayesClumpy posterior distribution outputs. The columns show each of the output parameters - $\sigma$, $Y$, $N_0$, $q$, $\tau_V$, $i$ - respectively. The solid vertical line marks the median value, while the dashed vertical lines mark the 1 $\sigma$ uncertainty.

| Parameter | Value |
|-----------|-------|
| $\sigma$  | 0.18  |
| $Y$       | 1.05  |
| $N_0$     | 1.23  |
| $q$       | 0.75  |
| $\tau_V$ | 0.05  |
| $i$       | 15.0  |

García-Burillo S., et al., 2016, ApJ, 823, L12
García-González J., et al., 2016, MNRAS, 458, 4512
Gendler R., et al., 1998, ApJ, 498, 579
Gonzalez Delgado R. M., Perez E., 1997, MNRAS, 284, 931
González-Martín O., et al., 2013, A&A, 553, A35
Granato G. L., Danese L., 1994, MNRAS, 268, 235
Gratadour D., Rouan D., Mugnier L. M., Fusco T., Clénet Y., Gendron E., Lacombe F., 2006, A&A, 446, 813
Groves B., Dopita M., Sutherland R., 2006, A&A, 458, 405
Haniff C. A., Wilson A. S., Ward M. J., 1988, ApJ, 334, 104
Hernán-Caballero A., et al., 2015, ApJ, 803, 109
Herter T. L., et al., 2012, ApJ, 749, L18
Ho L. C., 2009, ApJ, 699, 638
Ho L. C., Keto E., 2007, ApJ, 658, 314
Holtzman J. A., et al., 1992, AJ, 103, 691
Hönig S. F., Kishimoto M., Gandhi P., Smette A., Asmus D., Duschl W., Polletta G., Weigelt G., 2010, A&A, 515, A23
Hönig S. F., Kishimoto M., Antonucci R., Marconi A., Prieto M. A., Tristram K., Weigelt G., 2012, ApJ, 755, 149
Hönig S. F., et al., 2013, ApJ, 771, 87
Ichikawa K., Ueda Y., Terashima Y., Oyabu S., Gandhi P., Matsuka N., Nakagawa T., 2012, ApJ, 754, 45
Ichikawa K., et al., 2015, ApJ, 803, 57
Ichikawa K., Ricci C., Ueda Y., Matsuoka K., Toba Y., Kawamura T., Trakhtenbrot B., Koss M. J., 2017, ApJ, 835, 74
Jaffe W., et al., 2004, Nature, 429, 47
Jensen J. J., et al., 2017, MNRAS, 470, 3071
Kaiser M. E., et al., 2000, ApJ, 528, 260
Khachikian E. Y., Weedman D. W., 1974, ApJ, 192, 581
Kingham K. A., OConnell R. W., 1979, AJ, 84, 1537
Kinney A. L., Bohlin R. C., Calzetti D., Panagia N., Wyse R. F. G., 1993, ApJS, 86, 5
Kishimoto M., Kay L. E., Antonucci R., Hurt T. W., Cohen R. D., Krolik J. H., 2002, ApJ, 565, 155
Kishimoto M., Hönig S. F., Beckert T., Weigelt G., 2007, A&A, 476, 713
Kukula M. J., Ghosh T., Pedlar A., Schilizzi R. T., Miley G. K., de Bruyn A. G., Saikia D. J., 1993, MNRAS, 264, 893
Lebouteiller V., Barry D. J., Spoon H. W. W., Bernard-Salas J., Síoan G. C., Houck J. R., Weedman D. W., 2011, ApJS, 196, 8
Levenson N. A., Radomski J. T., Packham C., Mason R. E., Schafer J. J., Telesco C. M., 2009, ApJ, 703, 390
Li A., Draine B. T., 2001, ApJ, 554, 778
López-Gonzaga N., Burtscher L., Tristram K. R. W., Meisenheimer K., Schartmann M., 2016, A&A, 591, A47
López-Rodriguez E., et al., 2018, preprint, (arXiv:1804.04134)
Lu N. Y., Hoffman G. L., Groff T., Roos T., Lamphier C., 1993, ApJS, 88, 383
Malkan M. A., Gorkin V., Tam R., 1998, ApJS, 117, 25
Marconi A., Risaliti G., Gilli R., Hunt L. K., Maiolino R., Salvati M., 2004, MNRAS, 351, 169
Marinucci A., Bianchi S., Nicastro F., Matt G., Goulding A. D., 2012, ApJ, 748, 130
Martínez-Paredes M., et al., 2017, MNRAS, 468, 2
Martini P., Regan M. W., Mulchaey J. S., Pogge R. W., 2003, ApJS, 146, 353
Mason R. E., Geballe T. R., Packham C., Levenson N. A., Elitzur M., Fisher R. S., Perlman E., 2006, ApJ, 640, 612
Meléndez M., et al., 2008, ApJ, 682, 94
Figure 9. Top: Total FIR SED representation of the torus with starburst templates SB3 (Mullaney et al. 2011) scaled to the residual emission of NGC 4151 at 37.1 µm. Bottom: Total FIR SED of the torus with a 75 K blackbody. 70 and 100 µm Herschel fluxes within a 6-7" radius are shown as an upper limit to the total FIR emission. SOFIA residual fluxes are given as a lower limit.

Miller J. S., Goodrich R. W., Mathews W. G., 1991, ApJ, 378, 47
Mor R., Netzer H., 2012, MNRAS, 420, 526
Mor R., Netzer H., Elitzur M., 2009, ApJ, 705, 298
Mullaney J. R., Alexander D. M., Goulding A. D., Hickox R. C., 2011, MNRAS, 414, 1082
Mundell C. G., Holloway A. J., Pedlar A., Meaburn J., Kukula M. J., Axon D. J., 1995, MNRAS, 275, 67
Nagar N. M., Wilson A. S., Mulchaey J. S., Gallimore J. F., 1999, ApJS, 120, 209
Nenkova M., Sirocky M. M., Ivezić Z., Elitzur M., 2008a, ApJ, 685, 147
Nenkova M., Siroyck M. M., Ivezic Z., Elitzur M., 2008b, ApJ, 685, 160
Netzer H., 2015, ARA&A, 53, 365
Packham C., Radomski J. T., Roche P. F., Atikken D. K., Perelman E., Alonso-Herrero A., Colina L., Telesco C. M., 2005, ApJ, 618, L17
Pedlar A., Ghataure H. S., Davies R. D., Harrison B. A., Perley R., Crane P. C., Unger S. W., 1990, MNRAS, 246, 477
Pedlar A., Mukula M. J., Longley D. P. T., Muxlow T. W. B., Axon D. J., Baum S., O’Dea C., Unger S. W., 1993, MNRAS, 263, 471
Pedlar A., Fernandez-B, Hamilton N. G., Redman M. P., Dewdney P. E., 1998, MNRAS, 300, 1071
Peeters E., Spoon H. W. W., Tielens A. G. G. M., 2004, ApJ, 613, 986
Phillips M. M., Charles P. A., Baldwin J. A., 1983, ApJ, 266, 485
Pier E. A., Krolik J. H., 1992, ApJ, 401, 99
Pier E. A., Krolik J. H., 1993, ApJ, 418, 673
Quillen A. C., McDonald C., Alonso-Herrero A., Lee A., Shaked S., Rieke M. J., Rieke G. H., 2001, ApJ, 547, 129
Raban D., Jaffe W., Röttgering H., Meisenheimer K., Tristram K. R. W., 2009, MNRAS, 394, 1325
Radomski J. T., Piña R. K., Packham C., Telesco C. M., Tadhunter C. N., 2002, ApJ, 566, 675
Radomski J. T., Piña R. K., Packham C., Telesco C. M., De Buizer J. M., Fisher R. S., Robinson A., 2003, ApJ, 587, 117
Radomski J. T., et al., 2008, ApJ, 681, 141
Ramos Almeida C., Ricci C., 2017, Nature Astronomy, 1, 679
Ramos Almeida C., et al., 2009, ApJ, 702, 1127
Ramos Almeida C., Alonso-Herrero A., Levenson N. A., Asensio Ramos A., Rodríguez Espinosa J. M., González-Martín O., Packham C., Martínez M., 2014, MNRAS, 439, 3847
Riccì C., et al., 2017, preprint, (arXiv:1709.03989)
Rigby J. R., Diamond-Stanic A. M., Aniano G., 2009, ApJ, 700, 1878
Roche P. F., Atken D. K., Smith C. H., Ward M. J., 1991a, MNRAS, 252, 282
Rodríguez-Ardila A., Viegas S. M., 2003, MNRAS, 340, L33
Rodriguez-Ardila A., et al., 2017, MNRAS, 465, 906
Ruíz J. R., Crenshaw D. M., Kraemer S. B., Bower G. A., Gull T. R., Hutchings J. B., Kaiser M. E., Weistrop D., 2005, AJ, 129, 73
Sani E., et al., 2012, MNRAS, 424, 1963
Schartmann M., Meisheimer K., Camenzind M., Wolf S., Henning T., 2005, A&A, 437, 861
Schinnerer E., Eckart A., Tacconi L. J., 2000, ApJ, 533, 826
Schinnerer E., Eckart A., Tacconi L. J., 2001, ApJ, 549, 254
Schmitt H. R., Kinney A. L., 1996, ApJ, 463, 498
Schweitzer M., et al., 2008, ApJ, 679, 101
Siebenmorgen R., Krügel E., Spoon H. W. W., 2004, A&A, 414, 123
Siebenmorgen R., Heymann F., Elstathouli A., 2015, A&A, 583, A120
Smith J. D. T., et al., 2007, ApJ, 656, 770
Strauss M. A., Huchra J. P., Davis M., Yahil A., Fisher K. B., Tonry J., 1992, ApJS, 83, 29
Sturm E., Lutz D., Tran D., Feuchtgruber H., Genzel R., Kunze D., Moorwood A. F. M., Thornley M. D., 2000, A&A, 358, 481
Theureau G., et al., 2005, A&A, 430, 373
Tiff W. G., Cocke W. J., 1988, ApJS, 67, 1
Tommasin S., Spinoglio L., Malkan M. A., Smith H., González-Alfonso E., Charmandaris V., 2008, ApJ, 676, 836
Trippe M. L., Crenshaw D. M., Deo R. P., Dietrich M., Kraemer S. B., Rafter S. E., Turner T. J., 2010, ApJ, 725, 1749
Tristram K. R. W., et al., 2007, A&A, 474, 837
Tristram K. R. W., Burtscher L., Jaffe W., Meisenheimer K., Honig S. F., Kishimoto M., Schartmann M., Weigelt G., 2014, A&A, 563, A82
Uchida K. I., Sellgren K., Werner M., 1998, ApJ, 493, L109
Urry C. M., Padovani P., 1995, PASP, 107, 803
Vaona L., Ciroi S., Di Mille F., Cracco V., La Mura G., Rafanelli P., 2012, MNRAS, 427, 1266
Veilleux S., Bland-Hawthorn J., Cecil G., Tully R. B., Miller S. T., 1987, ApJ, 319, 716
Ward M., Elvis M., Fabbiano G., Carleton N. P., Willner S. P., Lawrence A., 1987, ApJ, 319, 716
Weedman D. W., et al., 2005, ApJ, 633, 706
Woo J.-H., Urry C. M., 2002, ApJ, 579, 530
Young E. T., et al., 2012, ApJ, 749, L17
de Vaucouleurs G., de Vaucouleurs A., Corwin Jr. H. G., Buta R. J., Paturel G., Fouqué P., 1991, Third Reference Catalogue of Galaxies

MNRAS 000, 1–17 (2018)
of Bright Galaxies. Volume I: Explanations and references.
Volume II: Data for galaxies between 0° and 12°. Volume III:
Data for galaxies between 12° and 24°.
van Bemmel I. M., Dullemond C. P., 2003, A&A, 404, 1

This paper has been typeset from a T\LaTeX/\TeX file prepared by
the author.