ISOTROPIC MID-INFRARED EMISSION FROM THE CENTRAL 100 PC OF ACTIVE GALAXIES

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ABSTRACT

Dust reprocesses the intrinsic radiation of active galactic nuclei (AGNs) to emerge at longer wavelengths. The observed mid-infrared (MIR) luminosity depends fundamentally on the luminosity of the central engine, but in detail it also depends on the geometric distribution of the surrounding dust. To quantify this relationship, we observe nearby normal AGNs in the MIR to achieve spatial resolution better than 100 pc, and we use absorption-corrected X-ray luminosity as a proxy for the intrinsic AGN emission. We find no significant difference between optically classified Seyfert 1 and 2 galaxies. Spectroscopic differences, both at optical and IR wavelengths, indicate that the immediate surroundings of AGNs is not spherically symmetric, as in standard unified AGN models. A quantitative analysis of clumpy torus radiative transfer models shows that a clumpy local environment can account for this dependence on viewing geometry while producing MIR continuum emission that remains nearly isotropic, as we observe, although the material is not optically thin at these wavelengths. We find some luminosity dependence on the X-ray/MIR correlation in the smallest scale measurements, which may indicate enhanced dust emission associated with star formation, even on these sub-100 pc scales.

1. INTRODUCTION

While active galactic nuclei (AGNs) present a variety of observational characteristics, unified models suggest that the central engines of all these objects are fundamentally the same. Accretion onto a supermassive black hole is the basic energy source, and an optically and geometrically thick surrounding “torus” introduces effects that depend on viewing geometry. In particular, spectrally broad emission lines are observed in type 1 AGNs, which afores a direct view of the fast-moving material close to the central engine, while the torus blocks the view of this broad line region in type 2 objects (Antonucci 1993).

The dust in the obscuring torus also reprocesses the intrinsic hard continuum radiation to longer wavelengths, and the bulk of it emerges in the mid-infrared (MIR) regime (5–30\textmu m). The observed MIR emission of AGNs thus is sensitive to the intrinsic bolometric luminosity of the AGN. High energy X-ray emission reveals the bolometric luminosity of the AGNs, and few other energy sources contribute substantially to these observed fluxes. Provided that measured 2–10 keV luminosities are corrected for intrinsic absorption, which can be significant, this X-ray luminosity is an effective proxy for the AGN bolometric luminosity, representing approximately 5\% of $L_{\text{bol}}$ (Elvis et al. 1994).

In detail, the spectral energy distribution of the reprocessed emission also depends on the geometric distribution of the dust. If the torus material is smoothly distributed, for example, the observed IR flux along unobscured lines of sight to the hot, optically-thin surface of the inner torus is much greater than that measured along lines of sight through the optically thick torus (Pier & Krolik 1992; Granato & Danese 1994; Efstathiou & Rowan-Robinson 1995). In contrast, if the dusty material is separated into clumps that do not fill the torus volume, the luminosity dependence on viewing angle is reduced (Hönig et al. 2006; Nenkova et al. 2008; Schartmann et al. 2008). MIR photometry of type 1 and 2 AGNs can therefore sensitively discriminate between smooth and clumpy dust distributions. Moreover, recent observations at high spatial resolution (Jaffe et al. 2004; Packham et al. 2005; Tristram et al. 2007; Radomski et al. 2008) suggest that the spatial scale of the dusty torus is small (< 10 pc). Thus, measurements of the torus emission must be made over limited physical regions, and comparison models must accommodate the small torus extent.

Previous work generally indicates that the intrinsic and reprocessed AGN emission are strongly correlated. However, some of these studies suffer from poor angular resolution (e.g., Lutz et al. 2004) and Ramos Almeida et al. (2007), for example, use MIR data from ISO. The spatial resolution of these observations is typically 2 kpc, and dust emission associated with star formation can contribute greatly on these scales. Observations with 8m class telescopes on the ground offer an order of magnitude greater angular resolution, but initial investigations provided only small samples (Krabbe et al. 2003; Horst et al. 2006). Extending the samples (e.g., Horst et al. 2008; Gandhi et al. 2009) introduced mixed classes of AGNs (including radio galaxies and LINERs, for example) which may have distinct properties because of their radio loudness and hardness of the ionizing continuum. Despite these complications, no earlier work shows significant differences between type 1 and 2 AGNs in the MIR. The spectral energy distributions of type 1 and 2 AGNs are characteristically different through the near-IR, with the former emitting much more strongly. The only suggestion of a difference between types in the...
MIR emerges at relatively short wavelengths ($\lambda = 6.7\mu m$; Ramos Almeida et al. 2007) and is not maintained in the longer-wavelength data of the same study (C. Ramos Almeida, private communication 2009).

In this paper we present MIR imaging of a sample of 17 Seyfert galaxies to compare with X-ray measurements of the AGN bolometric luminosity. We restrict this study to normal Seyfert galaxies, excluding radio-loud sources, in which non-thermal synchrotron emission can contribute significantly to the MIR flux. We require the sample galaxies to be closer than 50 Mpc, to achieve spatial resolution around 100 pc. In contrast with other work, we do not consider LINER galaxies, which may have unusual MIR properties (Elitzur & Shlosman 2000; Perlman et al. 2001). Moreover, we take particular care to correct the observed X-ray fluxes to recover the intrinsic AGN emission. The X-rays advantageously offer observations of emission that originates close to the black hole, avoiding the uncertainties of extinction corrections and variations among the more distant narrow line regions of optical [O III] measurements, for example. In addition, we directly compare our MIR results with radiative transfer calculations of dust emission.

2. OBSERVATIONS AND DATA REDUCTION

2.1. MIR Measurements

Observations were made using T-ReCS (Telesco et al. 1998) on the 8.1m Gemini South, Michelle (Glasse et al. 1997) on Gemini North, and OSCIR on the Blanco 4m at CTIO, Gemini North, and Gemini South. Table I shows the log of observations. OSCIR used a Boeing 128 $\times$ 128 pixel Si:As BIB detector, providing a plate scale of 0.183" per pixel on the 4m at CTIO. The spatial resolution achieved was around 1". Both T-ReCS and Michelle use a Raytheon 320 $\times$ 240 pixel Si:As IBC array, providing a plate scale of 0.089 and 0.1005" per pixel respectively, and achieved a spatial resolution of between 0.3 to 0.5". In the case of T-ReCS, the detector was used in correlated quadruple sampling (CQS) mode (Sako et al. 2003). In all cases, images were obtained using the standard chop-nod technique to remove time-variable sky background, telescope thermal emission and so-called “1/f” detector noise. For the T-ReCS observations, the chop throw was 15" and the telescope was nodded every 30 s, whereas Michelle was nodded every 45 s. The OSCIR observations had a chop throw of 30" on the 4m, but 15" on Gemini, and all telescopes were nodded every 30 s. The chop throw was typically at 0° (N-S), but was angled in the case of extended objects. Observations were made using the N ($\lambda_c = 10.36\mu m$, $\Delta \lambda = 5.27\mu m$), N' ($\lambda_c = 11.2\mu m$, $\Delta \lambda = 2.4\mu m$), S2 ($\lambda_c = 8.74\mu m$, $\Delta \lambda = 0.78\mu m$), or S15 ($\lambda_c = 11.6\mu m$, $\Delta \lambda = 1.1\mu m$) filters, where $\lambda_c$ is the central wavelength, and the filter width $\Delta \lambda$ indicates 50% cut-on and cut-off values.

Data were reduced using in-house developed IDL or equivalent Gemini IRAF routines. The difference for each chopped pair for each given nod-set was calculated, and the nod-sets were then differenced and combined to create a single image. Chopped pairs obviously compromised by cirrus, high electronic noise, or other problems were excluded. OSCIR, T-ReCS, and Michelle were mounted on the Cassegrain port of the telescopes so that north was up and east was left as projected onto the detector. In post-processing, images of the PSF stars were de-rotated to match the telescope pupil PA when the galaxy observations were observed. Image rotation is necessary because the projected angles of the telescope pupil (particularly the secondary mirror supports) rotate during observations (or pointings), having a significant effect on the low-level profile.

Both flux and point source function (PSF) standard observations were made for flux and image quality calibrations through the same filters used for each galaxy observation. Flux standards were observed using standard sources suggested from the Gemini web pages. We find that, consistent with other mid-IR observations, the uncertainty in the flux determination is around 10%. PSF observations were made using the same filters as the galaxy observations, immediately prior to or after the galaxy observations and used an identical setup to accurately sample the image quality. Short PSF or flux standard observations are comparable to longer source observations as the closed-loop active optics of Gemini and the mechanical stability offered by the 4m at the CTIO provides a similar PSF when taken at a similar telescope pointing and time. Observations of PSF and flux standards through the night showed a stable and consistent PSF.

We made three different photometric measurements of each nucleus. First, assuming that the peak emission represents the central source, we scaled the PSF to this peak. The scaled flux integrated over a region that fully encompasses the Airy disk is the “diffraction-limited” measurement, where diameters of 2" are typical of the observations from the 8.1m Gemini telescopes and 4" is appropriate for the observations from the 4m Blanco telescope. Second, we used a fixed physical scale defined by the resolution of the most distant galaxy, of 100 pc. Third, we estimated the flux of the unresolved nuclear component, the “PSF-fitting” measurement. In this case, we subtracted a scaled PSF from the galaxy image. The PSF scaled to the peak of the galaxy emission (the “diffraction-limited” measurement) represents the maximum contribution of the unresolved source. The residual of the total emission minus the scaled PSF represents the host galaxy contribution. [A detailed study of the extended near nuclear structures of the galaxies in our sample will be the subject of a forthcoming paper (J. T. Radomski et al., in preparation).] Subtraction of a PSF scaled to match the peak of the galaxy emission exactly results in an unrealistic minimum in the residual host galaxy emission. Instead, we reduce the scale of the PSF to produce a “flat” profile in the residual to obtain the unresolved fluxes reported in Table 2 (See Ramos Almeida et al. 2009 for examples of this technique.) We note that a flat nuclear profile may not account for any residual stellar cusp at the nucleus, but this effect will be small. For reproducibility and simplicity, we apply this approach to all of our sources. We estimate this method introduces a further uncertainty of 10–15% in the final flux measurements, which we add in quadrature to the flux calibration errors. In the case of the fixed spatial scale, a simple aperture was placed over the galaxy and the flux extracted. In all cases, a sky annulus was used to subtract low-level, residual sky emission not cancelled by the chopping and nodding.

While the observations were made through different
filters in the 10μm window, we assume a flat spectral energy distribution through the limited wavelength range they cover. Thus, we make no corrections to the measured fluxes in the comparisons below. We expect this simplified approach minimizes the introduction of additional uncertainties, given that we do not know in detail the high spatial resolution spectral energy distribution of each AGN. We have few of our own observations of Seyfert 1 galaxies, so we considered supplementing these with results from the literature. However, in order to compare the different MIR measurement techniques, we quote the statistical results from our sample alone.

2.2. X-ray Measurements

We take care that the X-ray measurements also isolate the AGN, favoring high angular resolution data. We prefer observations close in time to the MIR observations, to avoid possible complications of intrinsic AGN variability. All the X-ray fluxes are corrected for line of sight absorption (due to the host galaxy, or Milky Way, or both) to determine intrinsic luminosity in the 2–10 keV band, \(L_X\). The underlying AGN continuum of Compton thick galaxies, those obscured by \(N_H > 10^{24} \text{ cm}^{-2}\), does not emerge directly below 10 keV. In these cases, we prefer higher-energy observations to determine the AGN luminosity. These are generally uncontaminated by stellar processes, despite the poor angular resolution.

Table 2 lists the sample and basic data. The tabulated uncertainties reflect the range of observed luminosities, and genuine variability is significant in Seyfert 1s. The span of measured Seyfert 2 luminosities is usually small for each AGN, and we adopt a nominal 20% uncertainty to account for intrinsic variability if none is observed directly. When detection of a Compton thick AGN at \(E > 10\) keV is absent, the tabulated range indicates the uncertainty in the correction to recover the intrinsic luminosity. We use measurements from the literature where they are available. We present our own X-ray analysis of three galaxies below, and we give special consideration to the exceptional case of NGC 1068.

NGC 1068 is extremely optically thick, and the direct AGN emission is not detected even above 10 keV (Matt et al. 1997). In this case, the range of \(L_X\) indicates the uncertainty in determining the intrinsic luminosity. We use the results of Levenson et al. (2006), adopting the estimate of \(L_X\) from the Fe Kα line equivalent width (EW) and luminosity, and considering the fitted reflection model a lower limit, for \(D = 14.4\) Mpc. We use the estimate of Iwasawa et al. (1997), who consider the properties of the ionized scattering region, as an upper limit on \(L_X\).

NGC 1566 is included in the XMM slew survey and detected in both hard and soft bands in one observation (Saxton et al. 2008). Assuming \(\Gamma = 1.7\) (to apply the standard conversion from the survey count rate to flux) we have absorption-corrected 2–10 keV flux \(F_X = 5.8(\pm 2) \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}\).

We fit the ASCA spectrum of NGC 3081, using source and background screened events files from the Tartarus database. We simultaneously fit the 3–10 keV data from all four detectors, allowing for a constant offset due to calibration uncertainty. We ignore the softest energies because they do not directly reveal the intrinsic AGN output. Instead, they show significant line emission, suggesting a strong thermal or photoionized contribution. We fit the AGN as an absorbed power law, fixing photon index \(\Gamma = 1.9\), which is typical of Seyfert galaxies. We find \(N_H = 6.3(\pm 0.4) \times 10^{23} \text{ cm}^{-2}\), with absorption-corrected 2–10 keV flux \(F_X = 3.8(\pm 0.2) \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}\) averaged over all detectors.

We fit the Chandra spectrum of the nucleus of NGC 5728. The data were reduced as described in Levenson et al. (2006), and we used a 2′′ nuclear aperture. The direct continuum emission is strong. Fitting the data at \(E > 3\) keV and fixing \(\Gamma = 1.9\), we find \(N_H = 7.1(\pm 2) \times 10^{23} \text{ cm}^{-2}\), and \(F_X = 9.3(\pm 2) \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}\). The neutral Fe Kα line is also strong, having \(\text{EW} = 790\) eV.

3. RESULTS AND DISCUSSION

3.1. MIR and Bolometric Luminosity Correlations

Consistent with earlier similar work (Horst et al. 2006, 2008; Gandhi et al. 2009), we find overall that the X-ray and MIR luminosities are well-correlated. Because the X-ray measurements represent the intrinsic AGN luminosity, with minimal contamination from other sources in the host galaxies, we conclude that the MIR emission is strongly correlated with the AGN bolometric luminosity. This result holds for all three methods we employ to measure the MIR emission, and considering both intrinsic variability of the X-ray emission and using only errors on individual X-ray measurements. One simple way to quantify the strong correlation is to measure the unweighted mean (\(\mu\)) and standard deviation (\(\sigma\)) of \(\log L_{\text{MIR}}/L_X\). Using the diffraction-limited MIR luminosity we find \(\mu = 0.12\) and \(\sigma_r = 0.6\); in the PSF-fitted case we find \(\mu = 0.10\) and \(\sigma_r = 0.7\), and with the fixed physical aperture we find \(\mu = 0.37\) and \(\sigma_r = 0.5\). These values are comparable to the results of Gandhi et al. (2009), although we measure greater dispersion in the present smaller sample.

Despite the intrinsic high resolution of the diffraction-limited measurements, the differences with the PSF-fitted fluxes indicates that even on large telescopes, diffraction-limited MIR observations do not truly isolate the immediate dusty surroundings of AGNs, which are confined to smaller (< 10 pc) scales (Mason et al. 2006). Given that we cannot measure the torus by itself, the problem of \(L_{\text{MIR}}^{\text{dust}}\) is that the physical scale it encompasses varies among the different galaxies. Thus, while it offers a consistent technique from the observational viewpoint, the physical correspondence changes. The use of a fixed physical aperture directly compensates for this disadvantage, while reducing the effective resolution (for all but one galaxy). The PSF fitting offers the best determination of the flux of the unresolved MIR-emitting torus, despite the variation of physical scale from galaxy to galaxy. Thus, this result best describes the relationship between intrinsic AGN luminosity and the reprocessed emission of the torus.

The MIR luminosity of NGC 4945 changes greatly with the three different measurement techniques. This galaxy contains a strong starburst. Other sources of MIR emission in addition to the AGN are therefore significant on small scales, and these dominate even \(L_{\text{MIR}}^{\text{dust}}\); unlike in other galaxies. Also, because NGC 4945 is nearby, the fixed 100-pc aperture measurement covers a much larger area (that contains strong emission sources) than the
diffraction-limited (36 pc) region does.

The differences among the various MIR measurements are larger for the Seyfert 2 galaxies than for the Seyfert 1s. Among the latter, the PSF-fitting scales are all 90 or 100%, producing nearly the same result as the diffraction-limited measurements. The fixed physical aperture measurements remain similar for the Seyfert 1s. In contrast, PSF fitting of some Seyfert 2s implies that only a small fraction of even the unresolved emission is the torus. In these galaxies, other contributions remain significant on the 100 pc scale, as well.

Table lists the Spearman rank correlation coefficient and the corresponding probability, considering Seyfert 1, Seyfert 2, and total samples, and the three different MIR measurements separately. The correlations of the Seyfert 2 and full samples are significant; the less significant (though strong) correlation of the Seyfert 1 subsample alone is a consequence of the small number of objects. Figures through show the data and fitted functions, where X-ray variability contributes to the measurement uncertainty. The linear fits to the log-log MIR/X-ray relationships, while diffraction-limited or star formation rates (Davies et al. 2007). Considering the combined Seyfert 1 and 2 samples, both the diffraction-limited and PSF-fitting relationships suggest a dependence on luminosity, in the sense that is reduced with greater MIR emission. We attribute this result to contamination in the MIR, with additional components of dust emission associated with star formation present even on these small scales. Sources in addition to the AGN do not affect the X-ray data we use, while they do contribute to the MIR flux. The galaxies having excess MIR emission (the “contaminated” nuclei) are preferentially those with higher MIR luminosity. Moreover, this effect is reduced when using the fixed physical aperture MIR measurement, in which the absolute amount of contamination does not vary significantly among the different galaxies. We can interpret this result to mean that on scales of 100 pc, the star formation in all these galaxies is comparable. The luminosity dependence in the diffraction-limited and PSF-fitting results implies that the nuclear star formation (arising on even smaller scales) does vary. Star formation on such small scales in active galaxies has been directly measured at near-IR wavelengths, showing a range of specific star formation rates . Considering the MIR/X-ray relationships, while diffraction-limited or (especially) PSF-fitting measurements best reveal the reprocessed AGN luminosity of an individual galaxy, systematic differences introduce a luminosity dependence in the MIR/X-ray correlation that we do not attribute to properties of the AGN.

We note that the sense of the result of Gandhi et al. (2009) is similar to ours, though weaker, with . Thus, they do not claim any significant luminosity dependence in \( L_{\text{MIR}} / L_X \). While the luminosity

![Fig. 1.— The MIR emission, which the reprocessing torus dominates, is strongly correlated with AGN bolometric luminosity, which X-ray luminosity \( (L_X) \) indicates. Here we show diffraction-limited MIR measurements. Solid blue, red, and black lines show the linear fits to the Seyfert 1 galaxies alone, the Seyfert 2 galaxies alone, and all data combined, respectively. The uncertainty in the type 1 relationship is large, so the resulting fit is not significantly different from the type 2 or combined results. Observations of X-ray variability contribute to the effective error and are large for the Seyfert 1s, while uncertainty of the intrinsic X-ray emission from the very absorbed AGNs accounts for the largest errors in the Seyfert 2s. Measurement uncertainty dominates the MIR errors. Additional data from the literature are plotted (blue diamonds); they do not contribute to the fits but are consistent with them. The filled symbol is NGC 4945 , and dotted lines show theoretical predictions .](image1)

![Fig. 2.— As in Figure using PSF fitting of the MIR flux. The resulting fits are similar, and the correlation is again significant.](image2)
range of their sample is comparable, the average distance of their sources is greater. The luminosity effects we find are strongest in the measurements that best isolate the AGN torus, which may not be apparent at lower effective spatial resolution.

In contrast, Maiolino et al. (2007) found a luminosity dependence in the opposite sense, with MIR luminosity decreasing with increasing intrinsic AGN luminosity. That work investigated unobscured AGNs only, using lower spatial resolution observations from the Spitzer Space Telescope. Concentrating on more distant and higher luminosity AGNs, including quasars, however, they attribute the dependence to genuine differences in the torus as a function of luminosity. Specifically, if high-luminosity quasars partially clear their immediate surroundings, having less dusty material available to reprocess the intrinsic continuum would reduce the relative emergent MIR output. However, over the lower luminosity range we probe and utilizing high spatial resolution, contamination by star-heated dust is a stronger effect.

If we extend the sample of Seyfert 1s to include diffraction-limited measurements of nearby galaxies from the literature (Horst et al. 2006, 2008), the fitted functions remain consistent with each other over the different measurement techniques because of their large uncertainties. However, the strength and significance of the diffraction limited Seyfert 1 correlation is reduced, with $\rho = 0.53$ and $P = 0.13$. We plot these data in Figure 1 to show their overall agreement with our results, but the fitted relationships and statistical correlations of Table 3 do not use these measurements.

### 3.2. Isotropic MIR Emission from Clumpy Models

While a smooth optically and geometrically thick torus preserves the essence of AGN unification, accounting for viewing-angle dependent differences in the detectability of spectrally broad optical emission lines, it cannot accommodate the observed MIR isotropy. Detailed radiative transfer models (Pier & Krolik 1992; Granato & Danese 1994; Efstathiou & Rowan-Robinson 1995) all indicate significant differences in emergent MIR luminosity as a function of viewing angle for a given AGN luminosity. For any particular dust configuration, changes in viewing angle result in MIR luminosity differences of multiple orders of magnitude. Considering a range of simulated dust distributions, the resulting variation is even larger. Fundamentally, the type 1 AGNs are preferentially brighter in the MIR because they offer unobscured views of the hot optically thin surface of the inner throat of the torus. In contrast, obscuration of the central engines of type 2 AGNs simultaneously hides this hottest (most emissive) dust behind a large optical depth of cool material.

Clumpy torus models, in which the volume filling factor of the dusty material remains small, can readily account for the observed MIR isotropy while retaining the central features of AGN unification (e.g., Hönig et al. 2006; Nenkova et al. 2008b; Schartmann et al. 2008). The principal difference is that these configurations can pro-
vide direct views of some hot and some cold cloud faces from all lines of sight, even when the active nucleus itself is hidden. Thus, they reduce the sensitivity of MIR emission to viewing orientation, while simultaneously allowing for small tori and variability in line of sight obscuration.

We use the formalism and results of Nenkova et al. (2008a,b) to interpret these observations quantitatively. Individual clouds are optically thick in the V band, given by $\tau_V$, with the cool silicate dust of Ossenkopf et al. (1992). The average number of clouds along an equatorial ray is $N_o$, and they are distributed according to a power law in radius, $\propto R^{-q}$, from the dust sublimation radius, $R_d$, to an outer radius $R_o = Y R_d$. The “torus” is concentrated in the equatorial plane and has a smooth edge, with $\sigma$ setting the distribution in elevation; the average number of clouds along the line of sight $N_{\text{LOS}} = N_o \exp(-90^\circ - i)^2 / \sigma^2$ at inclination angle $i$ (measured from the pole).

Figure 4 presents the resulting MIR spectral energy distributions as a function of inclination angle for some characteristic parameter values. They show extremely little variation over all type 1 views ($i = 0$ to $30^\circ$). More importantly in the context of the present observations, the MIR continuum flux changes by only factors of a few from the extreme pole-on ($i = 0^\circ$) to equatorial ($i = 90^\circ$) lines of sight. One further consequence is that the silicate feature around 10\,\mu m can appear in emission (especially from type 1 views) or absorption (especially from higher inclinations), but it is generally weak, which is consistent with spectral observations (Hao et al. 2007; Thompson et al. 2009).

The emergent reprocessed MIR emission depends on the intrinsic AGN luminosity. We plot the theoretical MIR/X-ray correlations as dotted lines in Figures 4 through 3 for the characteristic parameters of Figure 4 (adopting $q = 2$). These model relationships have no luminosity dependence (i.e., the slope of the lines is one), and show the offset factor of a few between the extreme pole-on (blue) and equatorial (red) viewing angles. The absolute scale depends on the bolometric correction to an angular scale $\mu$ deg, and $\sigma$ on the bolometric correction to the MIR is sensitive to the total number of clouds in the torus, which $N_o$ and $\sigma$ govern. These parameters also determine the likelihood that the central engine is hidden. The less efficient reprocessors are more likely to be classified as type 1 AGNs, offering more obscured lines of sight. The effect of this selection bias is to reduce the net differences in MIR emission between AGN types. While for a given cloud distribution, type 1 views show increased MIR flux over their type 2 counterparts, the distributions that are more likely to be observed as type 1 have reduced MIR flux relative to the cloud configurations that are more likely to be observed as type 2. Observational samples remain small; so conclusions are not statistically robust, but they do suggest differences in the cloud distributions between AGN types (Ramos Almeida et al. 2009).

Observations indicate that typical values for parameters range over $N_o \sim 5–10$, $\sigma \sim 30–45^\circ$, and $\tau_V \sim 30–100$ (Nenkova et al. 2008a, and references therein). Specifically considering the 10 and 18\,\mu m silicate features together, Thompson et al. (2009) find $N_o \leq 6$, $\sigma = 45^\circ$, and $\tau_V \sim 30–60$. The MIR-emitting tori of the clumpy models are small. In terms of bolometric AGN luminosity in units of $10^{45}$\,erg\,s$^{-1}$, $L_{45}$, the outer radius $R_o \approx 0.4 Y \sqrt{L_{45}}$ pc, with $Y = 30$ or less. Even for the most luminous Seyfert galaxy of the sample, NGC 3281, $R_o \lesssim 7$ pc, assuming $L_{bol} = 20 L_X$ (Elvis et al. 1994). The torus is not resolved in direct imaging, despite the good angular resolution of large ground-based telescopes. NGC 4151 offers the most favorable combination of luminosity and proximity, yet here $R_o$ corresponds to an angular scale $\lesssim 0.07''$. This value is well below the diffraction limit of 0.27" at 8.8\,\mu m on an 8.1 m telescope. Intriguingly, resolving the torus may be possible on a 30m telescope, where $R_{0,8} = 0.074''$. MIR interferometry with MIDI at the VLTI currently offers sufficient resolution and has been used successfully to isolate AGN
isotropy is that the torus is simply optically thin in the luminosity dependence in the MIR/X-ray relationship. On scales smaller than 100 pc, the nuclear star formation produces the observed flux in the fixed physical aperture is (on median) 20% higher than the PSF-fitted value. On scales smaller than 100 pc, the nuclear star formation produces the observed luminosity dependence in the MIR/X-ray relationship.

One completely different explanation for the observed isotropy is that the torus is simply optically thin in the MIR, as Horst et al. (2008) considered. However, an optically thin torus would show 10 µm silicate emission in all cases, contrary to spectral observations. While silicate absorption attributable to the torus is generally weak, it is typical of type 2 AGNs, which requires optically thick material along the line of sight. (A smaller column in a cold foreground screen could alternatively account for the absorption, but this could not simultaneously be the source of the IR emission.) Furthermore, the Compton thick AGNs require total $\tau_V > 800$ along the line of sight (assuming standard gas-to-dust ratios). This value corresponds to total $\tau > 14$ at 8.8 µm, although dust-free gas (located within the dust sublimation radius) may also contribute to their X-ray absorption.

4. CONCLUSIONS

Intrinsic X-ray and reprocessed MIR luminosity of the active nuclei of Seyfert galaxies are strongly correlated. Emphasizing measurements at high spatial resolution, we find a luminosity dependence on the correlation over the range we probe when using two MIR measurement techniques that help to isolate the central unresolved emission. We attribute this effect to the presence of additional sources in the MIR, such as by emission by dust that young stars heat. Because this result emerges only using the two smallest scale measurements, it implies that significant nuclear star formation is present even on very small (sub-100 pc) spatial scales in these AGNs. However, we find no luminosity dependence in the MIR fluxes measured in fixed 100 pc apertures, suggesting that the stellar contributions on these scales are comparable in all galaxies.

We find no significant difference in the correlations between Seyfert 1 and Seyfert 2 galaxies, given the large (~factor of 10) uncertainty in the Seyfert 1 $L_{\text{MIR}}/L_X$ ratio. Thus, we conclude that the MIR emission of the AGN torus is nearly isotropic on all the small scales we probe here. We interpret these results as support for clumpy torus models, in which the MIR emission is insensitive to viewing angle because both illuminated and dark cloud faces contribute in part to observed flux over all viewing angles. In contrast, smooth obscuration models produce significantly stronger (by several orders of magnitude) MIR emission from type 1 AGNs, which exclusively allow direct views of the hottest dust surfaces.

We use numerical radiative transfer calculations to demonstrate explicitly the small differences in the spectral energy distributions for extreme pole-on (type 1) and edge-on (type 2) views of a clumpy torus. For typical model parameters, the MIR flux changes by less than a factor of 5 over all viewing angles. Considering a wide range of different cloud distributions, the observed variation is nearly always less than a factor of 20. Several factors that contribute to increasing the resulting isotropy include increasing the spherical symmetry of the cloud distribution, reducing the number of clouds along radial rays, and making the clumpy torus more compact. Furthermore, flux differences as a function of viewing angle decline at longer wavelengths.

While the clumpy models predict nearly isotropic MIR emission, selection effects may further contribute to minimizing the observed difference between AGN types, whose classification is sensitive to viewing angle. The tori of the AGNs that are most likely to be observed without obscuration reprocess the intrinsic emission less efficiently than those that contain more dusty clouds (which are more likely to be classified as type 2s). Consequently, the relative MIR flux of observed type 1s may be preferentially suppressed, while the observed type 2s may be preferentially MIR-enhanced.

An optically thin torus could account for the MIR isotropy, but it could not produce the observed spectral differences. Specifically, silicate absorption is typical of Seyfert 2s, and weak silicate features (in emission or absorption) are characteristic of Seyfert 1s. The clumpy torus is not optically thin in the MIR, which allows for these spectroscopic differences. Because both directly-illuminated and dark cloud faces contribute to the net observed spectrum, the resulting silicate features are always weak.

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Fig. 5.— MIR flux variation as a function of viewing angle. Each curve covers one clumpy dust distribution, and the flux is scaled to the value observed from the equatorial (edge-on) view. These results illustrate that the emergent 8.8 µm flux does not vary by more than factors of about 5 over all viewing angles, for typical parameter values ($N_0 \leq 6$, $\tau_V \leq 60$). Making the torus effectively more compact (increasing $q$) or making the cloud distribution more spherically symmetric (increasing $\sigma$) increase the MIR isotropy, as do decreasing $N_0$ and $\tau_V$.

### Table 1: Observation Log

| Galaxy    | Instrument | Telescope | Observation Date | Filter | On-Source Time (s) |
|-----------|------------|-----------|------------------|--------|-------------------|
| Circinus  | T-ReCS     | Gemini S  | 2004 Feb 01      | S12    | 565               |
| IC 5063   | T-ReCS     | Gemini S  | 2005 Jul 18      | S12    | 130               |
| NGC 1066$^b$ | Michelle | Gemini N  | 2004 Aug 10      | S15    | 4                 |
|           |            |           | 2005 Jan 31      | S15    | 4                 |
| NGC 1365  | OSCIR      | CTIO      | 1998 Feb 12      | N      | 482               |
| NGC 1386  | T-ReCS     | Gemini S  | 2003 Dec 06      | N      | 217               |
| NGC 1506  | T-ReCS     | Gemini S  | 2005 Sep 18      | S12    | 152               |
| NGC 2992  | Michelle   | Gemini N  | 2006 May 05      | N$'$   | 730               |
| NGC 3081  | T-ReCS     | Gemini S  | 2006 Jan 25      | S12    | 130               |
| NGC 3227  | Michelle   | Gemini N  | 2006 Apr 07      | N$'$   | 300               |
| NGC 3281  | T-ReCS     | Gemini S  | 2004 Jan 30      | N      | 261               |
| NGC 4151  | OSCIR      | Gemini N  | 2001 May 07      | N      | 360               |
| NGC 4388  | Michelle   | Gemini N  | 2006 May 12      | N$'$   | 549               |
| NGC 4945  | T-ReCS     | Gemini S  | 2006 Mar 17      | S12    | 261               |
| NGC 5506  | Michelle   | Gemini N  | 2006 Apr 06      | N$'$   | 546               |
| NGC 5728  | T-ReCS     | Gemini S  | 2005 Jul 08      | S12    | 130               |
| NGC 7172  | T-ReCS     | Gemini S  | 2004 May 13      | N      | 305               |
| NGC 7582  | OSCIR      | Gemini S  | 2001 Dec 13      | N      | 608               |

$^a$In guided beam only.$^b$ Both observations were used for flux calibration, with spatial profile measurements of only the 2004 data, obtained under better seeing conditions.
### TABLE 2
**NEARBY SEYFERT GALAXY SAMPLE**

| Galaxy        | z      | D (Mpc) | Type | $L_X^{a}$ (log erg s⁻¹) | $L_{MIR}^{b}$ (log erg s⁻¹) | $L_{MIR}^{c}$ (log erg s⁻¹) | $L_{MIR}^{d}$ (log erg s⁻¹) | PSF Scale (%) | X-ray Reference(s) |
|---------------|--------|---------|------|-------------------------|-----------------------------|-----------------------------|-----------------------------|---------------|---------------------|
| Circinus      | 0.0014 | 4.0 2.0 |      | 41.76⁺⁻0.08⁺⁻0.10     | 42.61                       | 42.57                       | 42.75                       | 90 1          |                     |
| IC 5063       | 0.0113 | 47.9 2.0|      | 42.93⁻⁻0.08⁺⁻0.12     | 43.57                       | 43.57                       | 43.61                       | 100 2         |                     |
| NGC 1068      | 0.0038 | 14.4 1.8|      | 42.78⁻⁻0.08⁺⁻0.18     | 44.04                       | 44.12                       | 44.34                       | 50 3 4        |                     |
| NGC 1365      | 0.0055 | 23.0 1.8|      | 42.18⁻⁻0.08⁺⁻0.08     | 42.82                       | 42.77                       | 42.83                       | 90 5          |                     |
| NGC 1386      | 0.0029 | 12.2 1.8|      | 41.81⁻⁻0.09⁺⁻0.08     | 41.73                       | 41.73                       | 41.77                       | 100 6         |                     |
| NGC 1566      | 0.0050 | 21.2 1.6|      | 41.50⁻⁻0.13⁺⁻0.18     | 41.73                       | 41.73                       | 41.77                       | 100 6         |                     |
| NGC 2992      | 0.0077 | 32.6 2.0|      | 42.18⁻⁻0.08⁺⁻0.08     | 42.82                       | 42.78                       | 42.85                       | 90 7          |                     |
| NGC 3081      | 0.0080 | 33.7 2.0|      | 42.71⁻⁻0.10⁺⁻0.08     | 42.58                       | 42.58                       | 42.60                       | 100 6         |                     |
| NGC 3227      | 0.0039 | 16.3 1.5|      | 42.28⁻⁻0.78⁺⁻0.08     | 42.53                       | 42.53                       | 42.50                       | 100 8 9       |                     |
| NGC 3281      | 0.0107 | 45.1 2.0|      | 43.18⁻⁻0.09⁺⁻0.09     | 43.49                       | 43.49                       | 43.61                       | 80 10         |                     |
| NGC 4151      | 0.0033 | 14.0 1.5|      | 42.94⁻⁻0.04⁺⁻0.09     | 43.00                       | 42.95                       | 43.08                       | 90 11 12 13   |                     |
| NGC 4388      | 0.0084 | 35.5 2.0|      | 42.88⁻⁻0.45⁺⁻0.06     | 42.94                       | 42.90                       | 42.95                       | 90 14 15      |                     |
| NGC 4945      | 0.0019 | 3.7 2.0 |      | 41.33⁻⁻0.08⁺⁻0.09     | 40.25                       | 39.25                       | 41.83                       | 10 16 17      |                     |
| NGC 5506      | 0.0062 | 26.1 1.9|      | 43.06⁻⁻0.65⁺⁻0.09     | 43.28                       | 43.28                       | 43.28                       | 100 18 19     |                     |
| NGC 5728      | 0.0094 | 39.5 2.0|      | 42.21⁻⁻0.07⁺⁻0.10     | 42.20                       | 42.20                       | 42.20                       | 100 6         |                     |
| NGC 7172      | 0.0087 | 36.7 2.0|      | 42.75⁻⁻0.34⁺⁻0.04     | 42.55                       | 42.51                       | 42.58                       | 90 19 20 21   |                     |
| NGC 7582      | 0.0053 | 22.2 2.0|      | 42.69⁻⁻0.08⁺⁻0.10     | 42.32                       | 42.23                       | 42.49                       | 80 22         |                     |

Additional galaxies:
- MCG -6-30-15 0.0077 32.7 1.2 42.59⁻⁻0.21⁺⁻0.21 43.09 43.09 43.09 23
- NGC 3783 0.0097 41.1 1.5 43.15⁻⁻0.17⁺⁻0.24 42.55 42.55 42.55 24 25
- NGC 4593 0.0090 38.0 1.0 42.88⁻⁻0.09⁺⁻0.08 42.41 42.41 42.41 26
- NGC 7314 0.0050 21.1 1.9 42.23⁻⁻0.10⁻⁺⁻0.29 41.69 41.69 41.69 27

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- a Absorption-corrected 2–10 keV X-ray luminosity. b Diffraction-limited aperture measurement. c Measurement from PSF fitting. d Fixed physical (100 pc) aperture measurement. e From Horst et al. (2008).

### TABLE 3
**CORRELATION RESULTS**

| Sub-Sample | $\rho$ | $\rho$ | $\rho$ | $\rho$ |
|------------|-------|-------|-------|-------|
|            | $\rho$ | $\rho$ | $\rho$ | $\rho$ |
| Diffraction Limited |       |       |       |       |
| PSF Fitting   |       |       |       |       |
| Physical Aperture |       |       |       |       |

**Note.** Spearman rank correlation coefficient, $\rho$, and two-sided probability, $P$. Linear fit parameters, for $\log(L_X) = a \log(L_{MIR}) + b$. 
