THE FIRST SPATIALLY RESOLVED MID-INFRARED SPECTRA OF NGC 1068 OBTAINED AT DIFFRACTION-LIMITED RESOLUTION WITH THE KECK I TELESCOPE

LONG WAVELENGTH SPECTROMETER

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ABSTRACT

We present spatially resolved mid-infrared (mid-IR) spectra of NGC 1068 with a diffraction-limited resolution of 0.25 using the Long Wavelength Spectrometer (LWS) at the Keck I telescope. The mid-IR image of NGC 1068 is extended along the north-south direction. Previous imaging studies have shown that the extended regions are located inside the ionization cones, indicating that the mid-IR emission arises perhaps from the inner regions of the narrow-line clouds instead of the proposed dusty torus itself. The spatially resolved mid-IR spectra were obtained at two different slit position angles, +8° and –13° across the elongated regions in the mid-IR. From these spectra, we found only weak silicate absorption toward the northern extended regions but strong absorption in the nucleus and the southern extended regions. This is consistent with a model of a slightly inclined cold obscuring torus that covers much of the southern regions but is behind the northern extension. While a detailed analysis of the spectra requires a radiative transfer model, the lack of silicate emission from the northern extended regions prompts us to consider a dual dust population model as one of the possible explanations in which a different dust population exists in the ionization cones compared to that in the dusty torus. Dust inside the ionization cones may lack small silicate grains, giving rise to only a featureless continuum in the northern extended regions, while dust in the dusty torus has plenty of small silicate grains to produce the strong silicate absorption lines toward the nucleus and the southern extended regions.

Subject headings: galaxies: active — galaxies: nuclei — galaxies: Seyfert — infrared: galaxies

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1. INTRODUCTION

Active galactic nuclei (AGNs) appear in a variety of types, which are often classified based on the presence of broad emission lines. Objects are classified as type I if both broad and narrow emission lines appear in their optical spectra and as type II if only narrow emission lines are present without broad emission lines. It is, however, a general belief that much of the observed diversity in the local universe arises from different viewing angles toward the central engine (CE) and a dusty toroidal structure around it, especially for Seyfert galaxies of types I and II. When the dusty torus is viewed face-on, both the CE and the broad-line regions can be seen directly, causing objects to appear as Seyfert 1 galaxies. When the dusty torus is viewed edge-on, the anisotropic obscuration created by the torus causes objects to appear as Seyfert 2 galaxies (see Antonucci 1993 for review). It is this crucial role played by dust in the unified model of AGNs that makes understanding dust properties very important in understanding AGNs.

A significant fraction of the optical/UV/X-ray luminosity of the active nucleus is absorbed by the proposed dusty torus and reradiated at mid-IR wavelengths. The infrared also suffers less extinction than the optical band and is preferred for probing the proposed dusty torus or dust in general in the nucleus. Early mid-IR observations of Seyfert galaxies (Roche et al. 1991) have shown that the 9.7 μm silicate feature appears in strong absorption in Seyfert 2 galaxies as expected from an edge-on geometry of the proposed dusty torus for type II objects. If the dust responsible for the 9.7 μm silicate feature belongs to the dusty torus, then the spatial distribution of the silicate absorption can provide very important clues to the physical properties (size, orientation, etc.) of the dusty torus.

It is, however, difficult to investigate the spatial distribution of dust in Seyfert galaxies because mid-IR emission from most Seyfert galaxies has not been resolved (see Gorjian et al. 2004). While thermal emission from hot dust has been considered as a dominant source of the mid-IR emission of Seyfert galaxies, the unresolved nature of the mid-IR image has left the discussion over a nonthermal origin still alive. NGC 1068 is one of a few Seyfert galaxies whose mid-IR emission is resolved. No other alternative mechanism like synchrotron radiation can produce emission over such an extended area, leaving heated dust grains as the likely source.

NGC 1068 is classified as a Seyfert 2 based on the presence of narrow emission lines and absence of broad emission lines. The detection of broad emission lines in polarized light (Antonucci & Miller 1985), however, has shown that NGC 1068 harbors an obscured Seyfert 1 nucleus. As one of the closest and brightest Seyfert 2 galaxies, NGC 1068 offers a better spatial scale for the detailed investigation of its obscured nucleus. NGC 1068 is at 14.4 Mpc (Tully 1988), so 1″ corresponds to 72 pc or 0.25 (our spatial resolution) corresponds to 18 pc in physical distance. As part of a greater mid-IR survey of a sample of Seyfert galaxies, NGC 1068 was selected specifically for the investigation of the physical properties of the proposed dusty torus.

NGC 1068 has been observed many times in the mid-IR in both imaging and spectroscopic modes. The spatially resolved mid-IR images of NGC 1068 show a linear structure covering...
about 1″ in the north-south direction (Braatz et al. 1993; Cameron et al. 1993; Bock et al. 2000; Tomono et al. 2001). Emission-line imaging of O [iii] showed that this disklike structure lies inside the narrow-line regions (NLRs; Evans et al. 1993; Macchetto et al. 1994). Since the NLRs are believed to be created by the ionizing radiation from the CE that is collimated by the dust torus, the dusty torus should be oriented in the east-west direction perpendicular to the narrow-line cones. Thus, this structure has been believed to be created by grains in the NLRs heated by the nuclear radiation. In this model, the dusty torus is then too cold to emit significantly at 10 μm.

While recent mid-IR imaging studies have provided some spatially resolved dust measurements in the nuclear region of NGC 1068, no spatially resolved spectra have been obtained in the mid-IR until this study. Mid-IR spectra of NGC 1068 have also been obtained repeatedly by several single-aperture ground-based telescopes and the Infrared Space Observatory (ISO) using various apertures, from 0′4 at VLTI to 24′′ × 24′′ at ISO (Lutz et al. 2000; Le Floch et al. 2001; Jaffe et al. 2004; Roche et al. 1991; Siebenmorgen et al. 2004). Most previous spectra show that the mid-IR spectra of NGC 1068 have significant silicate absorption. Especially Sturm et al. (2000) and Lutz et al. (2000) show the AGN-dominated spectra with no significant polycyclic aromatic hydrocarbon (PAH) emission lines.

A crude spatial map of the distribution of the silicate absorption has been provided by imaging studies using multiple narrow bands, most notably from Bock et al. (2000) and Galliano et al. (2003). However, these studies have given conflicting results making spatially resolved spectra necessary to resolve the issues. For example, Bock et al. (2000) have reported that the silicate feature is relatively strong in absorption on the nucleus and to the south but flat or even in emission to the north. In contrast, Galliano et al. (2003) found that the silicate feature appears strong in absorption to the north but either flat or in emission to the south. For the first time, we present the diffraction-limited mid-IR spectra of NGC 1068 at a spatial resolution of 0′25 to investigate the spatial distribution and the properties of dust in the nuclear regions.

2. OBSERVATION AND DATA REDUCTION

The mid-IR spectra of NGC 1068 were obtained on 2003 September 6 as a part of a larger mid-IR spectroscopic survey of nearby Seyfert galaxies. The low-resolution spectroscopic mode of the Long Wavelength Spectrograph (LWS; Jones & Puetter 1993) was used at the f/25 forward Cassegrain focus of the Keck I 10 m telescope. LWS uses a 128 × 128 pixel Boeing Si:As array with a spatial pixel scale of 0″08. For the present spectra, a slit with a 3 pixel width was used in the bottom 3′6 (45 pixels) of the array, giving 0″24 × 3″6 of slit size. The spectral dispersion is 0.0375 μm pixel⁻¹. The N-wide filter with a central wavelength of 10.1 μm was selected to give wavelength coverage of 7.71–12.48 μm. This wavelength range includes prominent PAH emission lines at 8.6 and 11.3 μm, as well as a wide silicate absorption line at 9.7 μm.

A log of our observations is presented in Table 1. The observations were made under excellent atmospheric conditions with low water vapor. Air masses varied between 1.06 and 1.11. The telluric absorption was measured by observing several standard stars, HR 337, HR 617, HR 8871, and HR 1017. The spectra of NGC 1068 were obtained at three different slit position angles, +8′0, +78′9, and −13′0, which were selected on the basis of both the direction of the extended mid-IR core and the location of bright guide stars. In LWS, the slit position angle on the sky is determined by the location of a bright offset guide star, which controls the telescope tracking. The guide star for the slit position angles of +8′0 and −13′0 were bright enough to give stable tracking. But the guide star at +78′9 was not bright enough, so tip-tilting errors were visible.

The standard “chop-nod” mode was used in the observation in order to suppress sky emission and radiation from the telescope. The field was chopped at a frequency of 2 Hz and nodded every 30 s. The chopping and nod directions were set to the same direction, parallel to the slit. The nodding amplitude was the same as the chopping amplitude of 10″. An individual spectrum set was created by co-adding a total of 60 frames with 50 ms integration time at each chop beam. These individual sets were then combined to produce seven nod sets per each run time with total on-source integration time of 168 s. Three run time spectra were acquired at each slit position angle for NGC 1068.

The raw spectra for both NGC 1068 and the standard stars were first sky-subtracted using the sky frame of the chop pair and flat-fielded. Bad pixels were replaced by the median of their neighboring pixels. The resultant spectra were then spatially rectified by a first-order polynomial before shifting the images parallel to the slit to align the peak position and in the direction of dispersion to align atmospheric absorption lines. After combining the images from each run-time set, a wavelength calibration was applied to them using atmospheric transmission lines1 with wavelengths calculated by Lord (1992).

The average spectrum of four standard stars was divided by a simulated blackbody spectrum with the star’s effective temperature and then divided into each run-time spectrum of NGC 1068 in order to remove atmospheric and instrumental features, including the deep ozone absorption band at 9.6 μm. HR 1017, a F5 star, was observed closest in time to NGC 1068 but at a worse air mass, 1.17. After many trials, we found that the average spectrum of all four standard stars yielded the best telluric correction in the spectra of NGC 1068. The upper panel of Figure 1 shows the mid-IR spectra of NGC 1068 at the nucleus divided by the spectrum of either HR 1017 or the average of four standard

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1 The actual data set of the atmospheric transmission lines was obtained from the Web site of the Gemini Observatory.
stars. The bottom panel displays the average spectrum of all four standard stars, as well as their individual spectra. When divided by the average spectrum, the spectrum of NGC 1068 looks much smoother in the short wavelength regions between 8.0 and 8.8 μm. The shaded regions in the top panel indicate the wavelength regions omitted from the fitting process. [See the electronic edition of the Journal for a color version of this figure.]

Before extracting the one-dimensional spectra of NGC 1068, 14 individual chop sets in each run-time set were inspected in order to check whether the seeing was stable throughout the exposure. Although three run-time sets were acquired at each position angle, only one run-time set was found to be stable at the slit position angles of +8°0 and -13°0. Thus, one-dimensional spatially resolved spectra were obtained by extracting consecutive three rows (0°25) in the spatial direction from the maximum emission of the single stable run-time set. For the total slit spectra, a total of 24 rows were combined to produce one-dimensional spectra from the average of three run-time sets. Once the one-dimensional spectra were extracted for each galaxy, we used a foreground screen model consisting of a power-law index, $s$, for $F_{\lambda} \sim \lambda^{s}$; a visual extinction, $A_v$; and the central wavelength, $\lambda_c$. We excluded the wavelength regions of strong atmospheric contamination and [S iv] emission ($\lambda = 10.511$ μm in the rest frame) and came up with the three wavelength intervals, 8.2–9.2, 9.8–10.4, and 10.6–12.4 μm that were used for the fit (Fig. 1). The silicate absorption profile was redshifted to match the observed spectra before the fitting process. We began with a very rough power-law fit to estimate the initial amplitude and the slope. We also get a rough estimate of the visual extinction and the central wavelength by eye. Then we ran a grid search to find a best fit to the observed spectrum. First, we started the search within ±40% of the initial values for the first three parameters in 1% increments. For the central wavelength, the iteration was run within ±2 μm from the best-guessed central wavelength in 0.1 μm increments. Then from the best-fit result of the initial search, we ran the grid search again with a 0.1% increment within ±20% of the revised center. Most times the fit converged, but sometimes it did not. Once the best fit was obtained, we measured the calculated $\chi^2$ ($\chi^2/N$) using the same three intervals that we used for the fitting to obtain the standard deviation of our spectra. The noise of our mid-IR data is background-limited and does not vary much outside the spectral region contaminated by atmospheric absorption. Three spectra with $\chi^2/N$ under unity suggest that the reduced $\chi^2$ value is perhaps underestimated by an overestimate of the noise in the spectra.

3. RESULTS

The mid-IR spectra of NGC 1068 were obtained at three different slit position angles, slit P.A. = +8°, +78°9, and -13°. The spectra along +8° and -13° slits were spatially resolved along the north-south elongated regions, while the spectrum along +78°9 slit was not extended. We present diffraction-limited total integrated fluxes along each slit position in Figure 2. The observed data are shown in a solid line, while the fit with the silicate extinction profile as a dashed line in each figure. For the spectra along +8° and -13° slits, we also display the relative flux from the central 0°25×0°25 rectangular region (CE) in the same figures for comparison. In each slit, the flux from CE accounts for a little more than a quarter of the total flux. As mentioned in the previous section, the spectrum along the +78°9 slit is noisier than the other two spectra due to a notable tracking problem from using a faint guide star. The two spectra along the north-south elongated regions look very similar to each other. They both have similar slopes and show significant silicate absorption (Figs. 2a and 2b). But the spectrum perpendicular to the north-south elongated regions looks steeper and has less silicate absorption than the others (Fig. 2c).

Overall, the mid-IR spectra of NGC 1068 are dominated by the broad silicate absorption line without strong emission features. Although not strong, [S iv] emission lines are apparent in all three spectra. We found that the silicate absorption lines are fit better with a small shift of the silicate absorption center. Given that the spectral resolution of our data is 0.11 μm, the shift is marginal ($\Delta \lambda \approx 2 \sigma$). The shifts may, however, be real as they all occur toward the shorter wavelength (see Table 2). Sturm et al. (2000) have reported a more significant shift in the broad silicate absorption feature centered at 9.4 μm in their ISO Short Wave-length Spectrometer (SWS) spectra of NGC 1068. But it was suspected that the contamination by the large ISO beam (various apertures between 14′′×20′′ and 20′′×33′′) might have caused the apparent blueshift of the silicate absorption center (Bock et al. 2000).

In Figure 3 we display our mid-IR spectrum (Keck LWS) and the UKIRT spectrum (Roche et al. 1991) on top of the ISO SWS spectrum (Lutz et al. 2000) of NGC 1068. For our spectrum in
The Keck LWS mid-IR spectrum of NGC 1068 was created by averaging two spectra along +8°C14 and +13°C013 slits and scaling to match the ISO SWS spectrum. The UKIRT spectrum is a reproduction of the mid-IR spectrum of NGC 1068 in Fig. 1 from Roche et al. (1991); \(F_{\nu}\) was first converted to \(F_{\nu}\) and then scaled to match the ISO SWS spectrum. Dr. Roche kindly provided his UKIRT data for this figure. The LWS spectrum matches both the UKIRT spectrum and the ISO SWS spectrum quite well, especially the depth of the silicate absorption. A better spatial resolution of NGC 1068 resulting from its proximity may explain why the AGN dominates the mid-IR flux of NGC 1068 in these spectra. D. Lutz kindly provided the ISO SWS data that were used for Fig. 1 in Lutz et al. (2000). [See the electronic edition of the Journal for a color version of this figure.]

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### Table 2

| Location       | Slit P.A. (deg) | Center (\(\mu\)m) | Index \(a\) | \(A_v\) | \(\chi^2/N\) |
|----------------|----------------|-------------------|------------|-------|-------------|
| North 4........... | +8             | 9.55              | 2.35       | 2.98  | 1.19        |
|                | -13            | 9.53              | 2.95       | 3.83  | 1.25        |
| North 3........... | +8             | 9.51              | 2.18       | 4.01  | 1.11        |
|                | -13            | 9.53              | 2.55       | 2.17  | 1.33        |
| North 2........... | +8             | 9.52              | 2.05       | 4.44  | 1.05        |
|                | -13            | 9.52              | 2.05       | 4.46  | 1.31        |
| North 1........... | +8             | 9.48              | 1.47       | 5.42  | 1.42        |
|                | -13            | 9.52              | 1.63       | 5.47  | 1.73        |
| Central engine... | +8             | 9.57              | 1.29       | 10.59 | 0.98        |
|                | -13            | 9.60              | 1.28       | 11.12 | 1.54        |
| South 1........... | +8             | 9.61              | 2.05       | 10.20 | 1.27        |
|                | -13            | 9.61              | 1.56       | 10.90 | 1.54        |
| South 2........... | +8             | 9.52              | 2.01       | 6.34  | 0.92        |
|                | -13            | 9.58              | 1.58       | 9.72  | 1.10        |
| South 3........... | +8             | 9.52              | 2.87       | 6.10  | 0.81        |
|                | -13            | 9.55              | 2.12       | 15.98 | 1.80        |

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Note: *The power-law index, \(a\), for \(F_{\nu} \sim \nu^{-a}\).*

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Figure 3, two spectra along +8°C and -13°C slits were averaged together and scaled to match the flux of the ISO SWS spectrum. The UKIRT spectrum is a reproduction of the mid-IR spectrum of NGC 1068 in Figure 1 from Roche et al. (1991); \(\lambda F_{\nu}\) was first converted to \(F_{\nu}\) and then scaled to match the ISO SWS spectrum. Our spectrum matches both the UKIRT spectrum and the ISO SWS spectrum quite well in both the depth and the slope of the silicate absorption feature, although each spectrum depicts a very different physical scale. Our Keck LWS spectrum represents the central 0°25 x 2° (18 x 140 pc in physical scale), while the UKIRT spectrum serves about 3 times and the ISO SWS spectrum about 10 times bigger areas in NGC 1068. In general, the mid-IR spectra of Seyfert 2 galaxies obtained with a large aperture show very different features than those with a small aperture. For example, an average ISO spectrum of 27 Seyfert 2 galaxies shows that strong PAH emission lines dominate the mid-IR regions (Clavel et al. 2000) due to contamination from host galaxy light. But the mid-IR spectra taken with small apertures display a significant silicate absorption feature without strong PAH emission lines (Siebenmorgen et al. 2004; Soifer et al. 2002; see Rhee & Larkin 2005 for further discussion). A better spatial resolution of NGC 1068 resulting from its proximity may explain why an AGN in NGC 1068 dominates both the ISO SWS and other small aperture spectra, revealing a significant silicate absorption without strong PAH emission lines. In their ISOCAM image of NGC 1068 (Fig. 2b), Le Floc’h et al. (2001) show that in NGC 1068 PAH feature at 7.7°C is very weak.

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\(^2\) The actual data from Roche et al. (1991) have ~15% less flux than what is shown in Fig. 1. The additional flux in ISO SWS spectrum may come from its larger aperture. The overall shape and the strength of the silicate feature of both spectra, however, agree with each other well.
within $\sim 10''$ circular radius from the nucleus but gets stronger farther out and peaks around 15'' away from the nucleus. If NGC 1068 were located at $\sim 20$ pc from the Earth as other typical Seyfert 2 galaxies, the ISO SWS spectrum would have easily included strong PAH features.

Our mid-IR spectrum (Keck LWS) as well as the UKIRT spectrum and the ISO SWS spectrum show, however, a stronger silicate absorption than ISOCAM-CVF spectrum of the nucleus of NGC 1068 does (see Fig. 4 in Le Floc'h et al. 2001). Applying the same screen model from Dudley & Wynn-Williams (1997), we found $A_v \sim 10$ mag, while Le Floc'h et al. (2001) reported $A_v \sim 7$ mag. It is not clear why the ISOCAM-CVF spectrum shows a flatter and less significant silicate absorption in the nucleus of NGC 1068. Rieke & Low (1975) have also reported a weak silicate absorption in NGC 1068. Their infrared spectrum of NGC 1068 was not, however, acquired from a spectroscopic observation but inferred from several narrowband photometry results. As discussed further in $\S$ 4, such a spectrum does not necessarily agree with the spectroscopic data.

For the $+8''$ and $-13''$ slit P.A.s, we extracted spectra from eight regions along the slit: four positions from the northern extended region, one position at the nucleus, and three positions from the southern extended region. Each spectrum represents the spectrum in a square beam of $0''25 \times 0''25$. In Figures 4 and 5, we overlay each slit on top of the 12.5 $\mu$m image by Bock et al. (2000) and present all eight spectra along each slit. Centered on the nucleus, the slit along $+8''$ crosses most of the northern extended region, all the way through the upper tongue in the northeast tip of the extended image. In the south, the slit along $+8''$, however, misses the bright southeast spot. The slit along $-13''$ covers the most extended regions well from the southern bright spot to the northern bright spot except for the upper tongue in the northeast. Figures 4 and 5 show that the spectra on the nucleus are bluer but get steeper away from the nucleus, indicating that the mid-IR continuum in the nucleus is dominated by hotter dust than dust off the nucleus. The $[S\ IV]$ emission line appears in all the extended regions, and the relative strength increases with the distance away from the CE.

The strength of the silicate absorption varies over the extended regions. It is strongest on the nucleus and declines to the north. This trend shows that our line of sight transmits through the largest amount of the cold dust toward the nucleus and intercepts...
less cold dust off from the nucleus. In addition, the silicate absorption remains relatively strong in the southern extended region but declines fast in the northern extended region as noted by Bock et al. (2000). This asymmetry may result from the northern opening of the torus being slightly tilted toward our line of sight. No silicate emission was detected in any region, contrasting with previous studies that had hinted at silicate line emission in the northern extended regions (Bock et al. 2000) or in the southern extended regions (Galliano et al. 2003). This is discussed further in § 4.

In the Appendix, we display individual spectra along each slit position in Figures 9–15 with brief explanations in the text. Each observed spectrum is represented by a solid line along with the best silicate extinction fit shown as a dashed line. In general, the fits are reasonable ($\chi^2/N \leq 2.0$) except in the spectral regions contaminated by strong atmospheric absorption lines (i.e., $\approx 8$ and $9.2–9.7 \mu m$). Table 2 summarizes the f parameters used to fit each individual spectrum. As discussed further in § 4, the best-fit parameters, especially $A_v$, should be taken with caution as the cold screen model may not apply to all the regions, especially in the north.

4. DISCUSSION

Previous imaging studies have produced local mid-IR spectral energy distributions (SEDs) and estimates of the silicate absorption by combining spatially resolved narrowband fluxes. Both Bock et al. (2000) and Galliano et al. (2003) provide such SEDs, which do not agree with each other. In the northern extended regions, Bock et al. (2000) show no silicate absorption but a smooth continuum, perhaps even silicate in emission. On the other hand, Galliano et al. (2003) find the silicate feature in absorption with a depth that increases with the distance from the CE. Our results do not, however, agree with either of the results above. Our spectra show that the silicate feature appears weak in absorption in the northern extended regions and with its depth decreasing with distance from the CE, instead of increasing as suggested by Galliano et al. (2003). In the southern extended regions, our spectra show significant silicate absorption in the southern extended regions consistent with that of Bock et al. (2000).

We believe such discrepancies arise because their local SED were synthesized from individual narrowband images observed

![Fig. 5.—Mid-IR spectra of NGC 1068 along a 13" slit overlaid on 12 \mu m deconvolved image of NGC 1068 from Bock et al. (2000). Each spectrum is produced from a 0.25 x 0.25 square beam and plotted in relative flux ($F_\nu$) as a function of wavelength ($\mu m$). In each set, the continuum is fit with a silicate extinction curve shown as a dashed line.](image)
at different times and may suffer variable seeing conditions. Under different seeing conditions, it is hard to compare accurately the fluxes of different bands. Our spectra do not, however, suffer from such uncertainty as all eight positions within an individual N-band spectra were obtained simultaneously.

The presence of the prominent structure to the north in the mid-IR image was used to indicate that the north axis of the torus opening is tilted toward our line of sight (Bock et al. 2000). The presence of strong silicate absorption toward the southern extended region supports this picture as it indicates obscuration from optically thick dust grains in the south. However, the presence of weak silicate absorption to the north is interesting. If we assume a simple torus model in which the northern opening is oriented toward us, then we might expect to see hot dust on the inner edge in emission assuming a similar dust composition as the obscuring material. We may not, however, have the same kind of cold foreground screen toward the hot diffuse dust in the north as to the nucleus and the south; thus, it is difficult to draw any firm conclusion by applying the same model to all regions and comparing the strength of the silicate features quantitatively based on the model fit such as the visual extinctions, $A_v$. A radiative transfer model is required to properly address the apparent differences in the strength of the silicate feature at various locations because dust temperature distribution and geometric effect affect the silicate feature amplitude. For non–spatially resolved mid-IR spectra of NGC 1068, many theoretical works have already been done using various radiative transfer models over the last couple of decades (Pier & Krolik 1992, 1993; Granato & Danese 1994; Granato et al. 1997; Rowan-Robinson 1995; Nenkova et al. 2002).

In the absence of a radiative transfer model, one may still consider a depletion of small grains within the elongated extended regions as one of the possibilities to explain the observed spectra in the north. The possible depletion of small grains in the AGN environment has been suggested by various authors (Maiolino et al. 2001; Weingartner & Murray 2002; Rhee & Larkin 2005). The fact that the northern extended regions reside inside the ionization cone renders further speculation. The formation of the ionization cone in NGC 1068 is discussed in three different ways by Bock et al. (2000): relativistic beaming, dust absorption, and electron scattering. In all three ways, the dust grains inside the ionization cones are directly heated by very strong UV radiation from the nuclear engine. This direct heating and other processes in the cone can destroy small grains. Figure 6 shows that only small grains less than 3 $\mu$m effectively give rise to the silicate feature seen in the mid-IR spectra of Seyfert galaxies. The effective destruction of small grains by strong nuclear radiation may explain the observed lack of silicate emission from the northern extended regions. The weak silicate absorption in the northern extended regions could be created due to absorption by cold dust grains puffed up from the torus between the observer and the hot dust grains that emit the continuum.

In contrast, the small grains in the cold outer regions of the dusty torus are shielded from and therefore survive the intense UV radiation. These small silicate grains can effectively absorb the continuum and create the silicate absorption feature observed in the mid-IR spectra of NGC 1068. Our spectra show that silicate absorption remains strong even to the location South 3. If the silicate grains responsible for the apparent silicate absorption belong to the dusty torus, this indicates that the dusty torus should extend at least tens of parsecs in a vertical direction. A recent interferometric mid-IR observation of NGC 1068, however, has revealed a parsec-scale structure believed to be the dusty torus (Jaffe et al. 2004). Perhaps the outer cold regions of a dusty torus do not radiate significantly at 10 $\mu$m because they are too cold. The parsec structure found in the interferometric image most likely comes from the heated inner regions of the dusty torus because the interferometric mid-IR spectra indicate the presence of cold small grains in the foreground by showing deep silicate absorption. It is possible that the outer radius of the torus reaches out to more than tens of parsecs. The dust distribution in the nuclear environment of NGC 1068 is summarized in Figure 7.

5. SUMMARY AND CONCLUSIONS

We used the Long Wavelength Spectrometer at the Keck I telescope with a 0"25 slit to obtain spatially resolved spectra of NGC 1068 at three different slit positions, slit P.A. = +8°, −13°, and +78°9'. Overall, our integrated spectra agree with the previous mid-IR spectra well. In NGC 1068, our resolved spectra showed that the silicate absorption was strongest on the nucleus (central engine), indicating that our line of sight transmitted through the largest amount of cold obscuring dust materials to the nucleus. Furthermore, the strength of the silicate absorption declines fast to the north but remains relatively strong to the south. This asymmetry in the strength of the silicate absorption as well as the larger extended emission regions to the north suggests that the north pole of the torus opening is inclined toward us and that the southern extended regions are behind the obscuring dusty torus. On the basis of the lack of strong silicate emission from the north, we considered the dual dust population model for AGNs in which two different dust populations exist in the ionization cones and in the dusty torus. The dust population in the ionization cones may lack small silicate grains or small grains in general and give rise to featureless continuum to the north, while the dust population in the dusty torus contains plenty of small silicate grains and causes the apparent deep silicate absorption lines to the nucleus and the south in NGC 1068. A detailed analysis using a radiative transfer model would provide a better understanding to our spatially resolved mid-IR spectra.

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as the cold screen model of the 9.7 μm silicate absorption feature used in this paper. We appreciate Dieter Lutz and Pat Roche for their ISO SWS and UKIRT spectra reproduced in Figure 3. Jamie J. Bock also kindly provided the images of NGC 1068 reproduced in Figures 4 and 5. We are grateful to Aigen Li for providing the code to produce Figure 6. We acknowledge useful conversations with Ari Laor, Matt Malkan, and Eric Becklin. J. R. thanks K. Cha and I. Song for their help in creating Figure 7.

APPENDIX

A1. MID-IR SPECTRA AT THE CENTRAL ENGINE

Figure 8 depicts the nuclear spectra of NGC 1068 at the central 0′′25 × 0′′25 location (central engine [CE]) along the +8″ slit in the top panel and the −13″ slit in the bottom panel. Produced essentially from the same region, they look almost identical but are at different relative flux levels. The spectra at the CE is the strongest overall and contain at least one-quarter of the total flux in the slit (see Fig. 2). The spectra at the CE rises at the short wavelength end, indicating that the nuclear flux at the mid-IR is dominated by hotter dust than dust off the nucleus. The silicate absorption is also strongest here, implying that the line of sight transmits through the largest amount of cold silicate grains. The silicate absorption line is best fit with the silicate extinction profile whose centers fall on 9.57 μm in the top panel and 9.60 μm in the bottom panel instead of 9.7 μm. A weak [S iv] emission line appears at 10.5 μm in both spectra.

A2. MID-IR SPECTRA AT NORTH 1

Figure 9 (North 1) shows the spectra of NGC 1068 at 0′′25 off the central peak to the north along the +8″ slit in the top panel and the −13″ slit in the bottom panel. Overall, they look similar to each other. Flux decreases significantly to about one-half of the CE, and the
spectra are much steeper. The silicate absorption is still significant but greatly reduced compared to the CE and even to South 1. Figure 9 shows that the silicate extinction profile fits the observed data extremely well at both slit positions. The best-fit centers of the silicate absorption lines are to the blue of the nominal wavelength in both panels. The \([\text{S} \text{ iv}]\) emission lines have a larger equivalent width than at the CE and appear at 10.5 \(\mu\text{m}\) in both spectra.

### A3. MID-IR SPECTRA AT NORTH 2

Figure 10 (North 2) shows the spectra of NGC 1068 at 0\(^{\circ}\)50 north of the central peak along the +8\(^{\circ}\) slit in the top panel and the −13\(^{\circ}\) slit in the bottom panel. In both panels, the spectra appear almost flat with weak silicate absorption in the middle. The flux drops to around 30% of the CE. The silicate extinction curve fit continues to match the observed data well with its center shifted to 9.54 \(\mu\text{m}\) in both the top and bottom panels.

### A4. MID-IR SPECTRA AT NORTH 3

Figure 11 (North 3) shows the spectra of NGC 1068 at 0\(^{\circ}\)75 off the central peak to the north along the +8\(^{\circ}\) slit in the top panel and the −13\(^{\circ}\) slit in the bottom panel. The spectrum in the top panel (from the +8\(^{\circ}\) slit) is approximately centered on the 12 \(\mu\text{m}\) feature called the “tongue,” which is to the north-northeast of the nucleus. In both spectra, the flux is around 5% of the CE. The silicate absorption continues to appear weak, while the relative \([\text{S} \text{ iv}]\) emission is stronger than in North 2.

### A5. MID-IR SPECTRA AT NORTH 4

Figure 12 (North 4) depicts the spectra of NGC 1068 at 1\(^{\circ}\)0 off the central peak to the north along the +8\(^{\circ}\) slit in the top panel and the −13\(^{\circ}\) slit in the bottom panel. Both spectra have low fluxes and appear noisy as they represent the regions outside the contours on the 12 \(\mu\text{m}\) map. The spectra rise toward the long wavelength. The \([\text{S} \text{ iv}]\) equivalent width is stronger than at any other region except South 3 along the −13\(^{\circ}\) slit.

### A6. MID-IR SPECTRA AT SOUTH 1

Figure 13 (South 1) depicts the spectra of NGC 1068 at 0\(^{\circ}\)25 south of the central peak along the +8\(^{\circ}\) slit in the top panel and the −13\(^{\circ}\) slit in the bottom panel. Even with a substantial decline in flux, the silicate absorption at South 1 remains as strong as that in the CE contrary to North 1 in which the silicate absorption drops significantly, indicating that a large amount of obscuring cold dust still
Fig. 9.—North 1: mid-IR spectra of NGC 1068. The top panel is from the slit along +8° and the bottom panel from −13°. Each spectrum is produced from a 0″.25 × 0″.25 square beam. In each set, the observed spectrum is fit with the silicate extinction curve. A dashed line represents the best fit and a dash-dotted line the fit with a center at 9.7 μm.

Fig. 10.—North 2: mid-IR spectra of NGC 1068. The top panel is from the slit along +8° and the bottom panel from −13°. Each spectrum is produced from a 0″.25 × 0″.25 square beam. In each set, the observed spectrum is fit with the silicate extinction curve. A dashed line represents the best fit and a dash-dotted line the fit with a center at 9.7 μm.
Fig. 11.—North 3: mid-IR spectra of NGC 1068. The top panel is from the slit along +8° and the bottom panel from −13°. Each spectrum is produced from a 0.25 × 0.25 square beam. In each set, the observed spectrum is fit with the silicate extinction curve. A dashed line represents the best fit and a dash-dotted line the fit with a center at 9.7 μm.

Fig. 12.—North 4: mid-IR spectra of NGC 1068. The top panel is from the slit along +8° and the bottom panel from −13°. Each spectrum is produced from a 0.25 × 0.25 square beam. In each set, the observed spectrum is fit with the silicate extinction curve. A dashed line represents the best fit and a dash-dotted line the fit with a center at 9.7 μm.
Fig. 13.—South 1: mid-IR spectra of NGC 1068. The top panel is from the slit along +8° and the bottom panel from −13°. Each spectrum is produced from a 0′′25 × 0′′25 square beam. In each set, the observed spectrum is fit with the silicate extinction curve. A dashed line represents the best fit and a dash-dotted line the fit with a center at 9.7 μm.

Fig. 14.—South 2: mid-IR spectra of NGC 1068. The top panel is from the slit along +8° and the bottom panel from −13°. Each spectrum is produced from a 0′′25 × 0′′25 square beam. In each set, the observed spectrum is fit with the silicate extinction curve. A dashed line represents the best fit and a dash-dotted line the fit with a center at 9.7 μm.
remains in the foreground. Here the amount of the shift in the centers of the silicate absorption lines in both panels are least among all the regions. The \([\text{S}\,\text{iv}]\) equivalent width appears as weak as at the CE.

A7. MID-IR SPECTRA AT SOUTH 2

Figure 14 (South 2) depicts the spectra of NGC 1068 at 0\(^\circ\)50 south of the central peak along the +8\(^\circ\) slit in the top panel and the −13\(^\circ\) slit in the bottom panel. The bottom spectrum presented in South 2 along the −13\(^\circ\) slit is from the southern bright knot in the 12 \(\mu\)m image, but the top spectrum along the +8\(^\circ\) slit is significantly to the west of the knot. In the bottom panel, the silicate absorption remains strong, and the flux rises in the short wavelength end like in CE. In contrast, the top panel shows that the silicate absorption is weak and the spectrum is flat. The centers of the silicate absorption lines appear blueshifted. The relative \([\text{S}\,\text{iv}]\) emission lines appear stronger than both at the CE and South 1 in both panels.

A8. MID-IR SPECTRA AT SOUTH 3

Figure 15 (South 3) depicts the spectra of NGC 1068 at 0\(^\circ\)75 south of the central peak along the +8\(^\circ\) slit in the top panel and the −13\(^\circ\) slit in the bottom panel. This position is below the lowest contour in the 12 \(\mu\)m image, and both spectra are noisy and the flux drops to 2% of the CE. In the top panel, the spectrum is very red and shows little silicate absorption. In the bottom panel, however, the spectrum is flat and displays strong silicate absorption. The relative \([\text{S}\,\text{iv}]\) emission lines have higher equivalent width than in South 2.

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