1. INTRODUCTION

Physics around black holes, including accretion of material and launching of jets, has been a fundamental question in astronomy for a long time (e.g., Eardley & Press 1975). It is not yet clearly known how accreting material disposes of its angular momentum while falling into a black hole, how and where a jet is launched from around a black hole. With a jet of a 100 pc scale observed (e.g., Gallimore et al. 1996), active galactic nuclei (AGNs) of Seyfert galaxies are the best targets to attack the mystery of accreting material and jets.

There are two classes of Seyfert galaxies: Seyfert 1 and Seyfert 2. They have similarities and differences in, for example, their visible spectra, which are commonly known to be explained with the unified model (Antonucci 1993). According to the unified model, an AGN has a black hole at its heart. Material falls down into the black hole through an accretion disk while emitting X-ray and UV light. Throughout this paper, we define the system of the black hole and the accretion disk as the “central engine,” following Galliano et al. (2003). The unified model proposes three classes of clouds around the central engine. First, narrow-line regions (NLRs) spread over ∼100 pc and emit permitted and forbidden lines with velocity widths of ∼1000 km s⁻¹. Second, broad-line regions (BLRs) in the vicinity of the central engine emit permitted lines of H/C₂ and forbidden lines with velocity widths of 10,000 km s⁻¹. Third, an opaque compact but geometrically thick dusty torus around the central engine hides the direct view to the central engine and its BLRs from our line of sight when the central engine is viewed through the torus. The dusty torus is the key to the unified model, because it is what distinguishes Seyfert 1 and Seyfert 2. Seyfert 2 nuclei are viewed through the dusty torus, and BLRs are only seen in scattered light.

NGC 1068 is one of the nearest Seyfert 2 galaxies. Many observations have revealed various features that confirm the unified model: an accretion disk of 1 pc scale (Gallimore et al. 1997, 2001), the Seyfert 1 nucleus seen in polarized light (Antonucci & Miller 1985), and NLRs (Evans et al. 1991). However, no clear image of the dusty torus has been obtained (e.g., Bock et al. 2000; Tomono et al. 2001; Rouan et al. 2004). Only recently, Jaffe et al. (2004) found a 2.1 pc scale emission component of warm (320 K) dust surrounding a more compact hot (∼800 K) dust component with the Mid-Infrared Interferometric Instrument coupled to the Very Large Telescope Interferometer. They identified the hot component as the inner wall of the dusty torus. This is a step toward clear images of the dusty torus, including its temperature structure, density distribution, and relations with structures in larger and smaller scales.

On the other hand, the inner radii of the dusty tori are being measured with reverberation mapping. This method measures the lag time of light curves of an AGN in the V band and those in the K band. In reverberation mapping, the measured lag time is interpreted as the time duration in which light from the AGN reaches the inner wall of the dusty torus. Multiplying the lag by the speed of light, the inner radius of the dusty torus Rₘₐₜ can be obtained. Minezaki et al. (2004) found a good correlation between lags and absolute magnitudes in the V band in a number of Seyfert 1 galaxies. This implies that Rₘₐₜ is governed by the luminosity of the central engine. Adopting their results, the minimum Rₘₐₜ for NGC 1068 is estimated to be ∼0.045 pc from mᵥ ~ 11.5 mag (Sandage 1973). The estimated radius is consistent with the upper limit of 1 pc measured by Jaffe et al. (2004). The method seems to be promising for unveiling the innermost structures of dusty clouds around AGNs. However, we have to note that the results do not necessarily require the dusty clouds around the AGNs to be in the shape of a torus. It is still critical to obtain direct images of dusty tori.

It is best to look for a dusty torus in the infrared (IR). First, from thermal equilibrium, it is expected that dust in a torus of...
10 pc scale radiates mainly around 10 μm (Pier & Krolik 1992). Next, there are absorption/emission features of carbonaceous dust at 3.4 μm and of silicate dust at 9.7 μm. Comparison of the dust features may be used to probe the temperature structure of a dusty torus, as has been suggested by Imanishi (2000). Because L-band emission is dominated by dust at ~1000 K, the 3.4 μm absorption feature should originate from the dust clouds within a few pc from the central engine (Pier & Krolik 1992). On the other hand, the 9.7 μm absorption feature only measures the extinction toward the outer region of the dusty torus, because dust of ~300 K, which is the dominant source of the mid-infrared (MIR) emission, is located farther out from the heating source. Therefore, the combination of MIR spectra (8–13 μm) and L-band spectra (2.8–4.2 μm) would probe the temperature distribution of dust in the line of sight through the dusty torus.

This paper reports the results from observations of NGC 1068 in the MIR and in the L band with the Subaru Telescope, which is best suited for this study with its superb image quality in IR. Two instruments, the Mid-Infrared Test Observation System (MIRTOS) and the Infrared Camera and Spectrograph (IRCS), were used with the fine pixel scales optimized for the image quality of the telescope. The remainder of this paper is organized as follows: §§ 2 and 3 describe observations and data reduction in the MIR and in the L band, respectively; § 4 discusses emission mechanisms of the continua, spectral and spatial change of the dust features, and distributions of warm dust clouds; and § 5 summarizes the results. Throughout this paper, we assume a redshift of 0.0038 for NGC 1068 (Bottinelli et al. 1990). One arcsecond corresponds to 72 pc at the distance of NGC 1068, assuming a Hubble constant of \( H_0 = 75 \) km s\(^{-1}\) Mpc\(^{-1}\). Galliano et al. (2003) measured positions of the various spatial structures in the NGC 1068 nucleus observed at different wavelengths and found that the central engine is at the IR peak. We employ their registration to compare the results in the MIR and in the L band, as well as those in the literature.

2. MIR DATA

2.1. Observations

MIR imaging observations of NGC 1068 with the “silicate filters” (\(\lambda/\Delta\lambda \sim 10\)) at 7.7, 8.8, 9.7, 10.4, 11.7, and 12.3 μm were made on 1999 December 31, 2000 January 9, and 2000 January 18 UT. We used the MIRTOS (Tomono 2000; Tomono et al. 2000) mounted at the Cassegrain focus of the 8.2 m Subaru Telescope. The pixel scale was 0.0067, corresponding to a projected distance on the sky of 4.8 pc at the distance of NGC 1068. Sequences of 96 images of 31 ms integration were obtained. Between the sequences, the telescope was nodded typically 30° to the north to acquire background images. In this study, the data described in Tomono et al. (2001) were reduced again with the higher computing power available today.

2.2. Shift-and-Add and Registration of Images

Many short-exposure images with a 31 ms integration time were shifted and added to construct high-resolution images in each filter. First, background images, which were made by averaging the short-exposure images in the nodding pair, were subtracted from the raw images. Second, bad pixels and detector-array-specific features were corrected. Third, the peak position of the object in each image was measured with a precision of one tenth of a pixel with Gaussian fitting. The FWHM of the Gaussian was fixed to be the same as that of the Airy pattern to pick up the brightest speckle. Fourth, each pixel of the images was divided into 10 times 10 pixels, resulting in a pixel scale of 0.0067. Fifth, each image of the smaller pixel scale was shifted by registering the peak position measured in the third step. Finally, the shifted images were averaged after some images with low peak values were removed. Table 1 summarizes the total integration time of the short-exposure images used and the ratio of the images used to those acquired.

The flux was calibrated with the standard star \( \alpha \) Ari (Cohen et al. 1999). The flux uncertainty was estimated at about 9% from the measurement of the other standard star \( \alpha \) CMa (Cohen et al. 1995).

The shifted and added image of each filter was registered and convolved to have the same FWHM of ~0.37 (26 pc) as follows. The peak position of the object for each filter was measured by Gaussian fitting of the pixels with fluxes of more than 75% of the peak. The images were registered assuming that the peaks for each filter are at the same location on the sky (Galliano et al. 2003). The images are then Gaussian convolved so that all the images have a similar FWHM. Figure 1 shows the spatially integrated

| Wavelength (μm) | Total Integration Time of Images Used (s) | Percentage of Images Used (%) |
|----------------|------------------------------------------|------------------------------|
| 7.7-------------| 2.7                                      | 23                           |
| 8.8-------------| 5.2                                      | 43                           |
| 9.7-------------| 4.9                                      | 41                           |
| 10.4-----------| 24.9                                     | 42                           |
| 11.7-----------| 53.7                                     | 53                           |
| 12.3-----------| 68.2                                     | 47                           |

![Fig. 1.—SED and results of graybody fitting in the MIR (lower data points, curves, and left axis) and flux densities in a 3.8′′ aperture (upper data points and right axis) compared with the spectrum measured with the ISO SWS (Sturm et al. 2000, right axis). Each spatial element is measured in an area 0.75 long (P.A. of 3′) by 0.3′ wide corresponding to the L-band slitlet. Each data point is shown with the filter path band as a horizontal error bar and a flux uncertainty of ±1 σ, including uncertainty in the flux conversion factor, as a vertical error bar. The thick curves display the resulting graybody models (eq. [1]) on respective spatial elements. The dotted curve shows the underlying model continuum for the peak. The 10.4 μm data are not used in fitting (see § 4.2).](image-url)
spectral energy distribution (SED) within a 3.8’’ diameter aperture on the registered narrowband images. The *Infrared Space Observatory* Short Wavelength Spectrometer (ISO SWS) spectrum in the 14’’ × 27’’ aperture (Lutz et al. 2000; Sturm et al. 2000) is also shown for comparison. The flux densities measured from the MIRTOs images are consistent with the flux density of the continuum in the SWS spectrum.

2.3. Graybody Fitting

We fitted the MIR SED with a graybody emission model including the silicate feature to estimate the temperature and amount of MIR-emitting dust, as well as the optical depth of the silicate absorption/emission feature. It should be noted that the extracted parameters do not represent all the physical conditions but only characterize distributions of dust in some aspects, as described below. The observed SED was fitted with a model flux

\[ F_\lambda(\lambda) = \varepsilon_{\text{cont}} \left( \frac{\lambda}{10 \ \mu\text{m}} \right)^{-n} B_\lambda(T_{\text{cont}}, \lambda) \exp \left[ -\tau_{9.7} k(\lambda) \right], \]

where \(B_\lambda(T, \lambda)\) is the Planck function of temperature \(T\) and \(k(\lambda)\) is the optical depth of the silicate feature obtained from the IR excess toward \(\mu\) Cep (Roche & Aitken 1984) and normalized at 9.7 \(\mu\text{m}\).

The \(\mu\) Cep extinction curve is used in this work to compare the silicate feature with the 3.4 \(\mu\text{m}\) feature, as has been done by Roche & Aitken (1984). The 7.7 \(\mu\text{m}\) image was not used, because the IR excess data do not cover the short wavelength. The peak wavelength of the silicate absorption feature seen in the SEDs in Figure 1 is different from that observed toward \(\mu\) Cep: the peak wavelength of the absorption is shifted from 9.7 to 10.4 \(\mu\text{m}\), especially at the central peak. Because of this, the 10.4 \(\mu\text{m}\) image was not used in the SED fitting. See §4.2 for a discussion on the change of the peak wavelength.

The variables \(T_{\text{cont}}, \varepsilon_{\text{cont}},\) and \(\tau_{9.7}\) were treated as free parameters for the fitting. The color temperature \(T_{\text{cont}}\) represents the temperature of the warm dust grains emitting the MIR continuum (see §4.1.1 for a discussion). The factor \(\varepsilon_{\text{cont}}\) is a product of the dust emissivity at 10 \(\mu\text{m}\) and the beam filling factor of warm dust grains of \(T_{\text{cont}}\). Throughout this paper, we call \(\varepsilon_{\text{cont}}\) the “emissivity.” The mass of the warm dust grains per unit area can be estimated as \(M_{\text{dust}} = \varepsilon_{\text{cont}}/K_{\text{abs}}\), where \(K_{\text{abs}}\) is the absorption cross section per unit mass of dust grains. The dust model (Weingartner & Draine 2001; Draine 2003) with \(R_\text{p} = 5.5\) tabulates the absorption cross section at 10 \(\mu\text{m}\) as \(K_{\text{abs}} = 0.40 \text{ cm}^2 \text{g}^{-1}\). Although the dust cloud might be clumpy, clumpiness does not affect the mass estimation when \(\varepsilon_{\text{cont}} < 1\) and a homogeneous temperature is assumed of the warm dust that is emitting continuum. The other free parameter, \(\tau_{9.7}\), is the optical depth of the silicate feature at 9.7 \(\mu\text{m}\) toward the warm dust that is emitting continuum. A negative optical depth in our model represents emission of the silicate feature. Although the spectral index of dust emissivity \(n\) is usually uncertain, ranging from 1 to 2, we assumed \(n = 1.6\) following Cameron et al. (1993). Figure 2 shows spatial distributions of the parameters fitted on each pixel. The images were successfully fitted over a region of 50 pc to the north and 40 pc to the south from the central peak: the uncertainties in the fitted parameters are \(\Delta \tau_{9.7} < 1\), \(\Delta T_{\text{cont}} < T_{\text{cont}}/2\), and \(\Delta \varepsilon_{\text{cont}} < \varepsilon_{\text{cont}}/2\). Using the secondary reference star \(\alpha\) CMa rather than \(\alpha\) Ari, the resulting \(T_{\text{cont}}\) is within 1.5 K, \(\tau_{9.7}\) becomes about 0.1 deeper, and \(\varepsilon_{\text{cont}}\) becomes 10% stronger. To improve the signal-to-noise ratio of the parameters in the area surrounding the central peak, the data were also fitted after being convolved to have a 1.4 times wider FWHM.

Maiolino et al. (2001) pointed out that ground-based measurements of the silicate absorption feature at 9.7 \(\mu\text{m}\) might suffer from contamination in the continuum with the unidentified infrared band (UIB) emission at 7.7 \(\mu\text{m}\). However, Sturm et al. (2000) detected little emission of the 7.7 \(\mu\text{m}\) UIB toward NGC 1068 with ISO SWS in the 14’’ × 27’’ aperture. The 3.3 \(\mu\text{m}\) UIB feature is not seen in the spectrum obtained toward NGC 1068 by Imanishi et al. (1997) with the 3.8’’ aperture nor in the L-band spectra in this work. In fact, the UIBs detected with ISOCAM (ISO Camera; Le Floc’h et al. 2001) originate almost exclusively from the starburst regions, peaking at a distance of 1 kpc (14’’) from the central engine. They indicated that the AGN contributes less than ~5% to the total integrated UIB emission. Therefore, we concluded that the contamination by the UIBs to the continuum is negligible in our field of view of ~200 pc (27’’) around the central engine of NGC 1068.

High-temperature areas seen 0.34’’ from the central engine on the east and west sides coincide with the second and third diffraction rings (0.29’’ and 0.41’’ radius) of the Airy pattern at 8.8 \(\mu\text{m}\). Between these diffraction rings, there are also diffraction rings at longer wavelengths that might affect the fitting. Nevertheless, a fitting on convolved Airy images does not reproduce a peak in the fitted temperature. Therefore, we concluded that the high-temperature region is not an artifact induced by the Airy rings.

The flux was also spatially integrated over the area of each L-band slitlet (see §3.2), and the integrated flux is fitted with the same model as described in equation (1). With comparable spatial resolutions achieved for the MIR shifted and added images and the L-band seeing-limited spectra, no further convolution or deconvolution was performed. The results are shown in Figure 1.
3. L-BAND DATA

3.1. Observation

A seeing-limited spectroscopic observation of NGC 1068 in the \( L \)-band was conducted on 2000 September 24 UT. We used the IRCS (Tokunaga et al. 1998; Kobayashi et al. 2000) mounted at the Cassegrain focus of the Subaru Telescope. The \( L \)-band grism for 2.8–4.2 \( \mu m \) was used with the 0\(^{\prime}\)3 slit, yielding a spectral resolution of \( \lambda/\Delta \lambda \sim 400 \). The length of the slit was 18\(^{\prime}\). The pixel scale was 0\(^{\prime\prime}\)058 pixel\(^{-1}\). NGC 1068 was observed with a slit position angle (P.A.) of 3\(^{\prime}\) from the north, with the slit positioned at three positions to map the central region of the central peak: pointing offsets of \( \pm 6 \)\(^{\prime\prime}\) along the slit and 0\(^{\prime\prime}\)28 and 0\(^{\prime\prime}\)56 to the east were applied. The positions of the slits are illustrated in Figure 2a. We call the slit at the central peak slit C, and the slits in the east 0\(^{\prime\prime}\)28E and 0\(^{\prime\prime}\)56E according to the offsets to the east in arcseconds. Eight exposures of 2 s of on-source integration time were obtained for each slit position. The sky condition was photometric throughout the observation. The air mass to the target was 1.09 ± 0.01. From the size of the image along the slit, the spatial resolution was estimated to be 0\(^{\prime\prime}\)31 or 22 pc in FWHM. As a telluric standard, a spectrum of BS 813 was obtained at a similar air mass (1.08). We selected an F-type star as a telluric standard, because it is known that no strong stellar absorption lines are present in the \( L \)-band for F-type stars. For flat fielding, spectra of the dawn sky were obtained at the end of the night.

3.2. Data Reduction

The \( L \)-band data were reduced following the standard procedure: the two-dimensional spectrograms were background subtracted by the dithering pairs, flat fielded, and corrected for bad pixels using IRAF.\(^2\) Subsequently, positional shifts of the spectrograms of each slit position were measured with cross-correlations and confirmed to be not more than 0.2 pixels (0\(^{\prime\prime}\)01 or 3.2 \( \lambda \)) in both the spatial and dispersion directions. The spectrograms were shifted in the dispersion direction on the two-dimensional spectrograms to cancel wavelength shifts between the slit positions. The fluxes of the spectrograms were then calibrated with the spectrum of the standard star BS 813, which was assumed to have an effective temperature of 7244 K (Johnson & Wright 1983). Wavelengths of the spectra were calibrated using cross-correlation with a model atmospheric transmittance (Rothman et al. 1998). Then, the spectra in slitlets of 0\(^{\prime}\)15 along the slit were extracted to examine spatial variations. Finally, the spectra were convolved with a Gaussian with a FWHM of 8.2 \( \lambda \) in the dispersion direction to match the spectral resolution to that of the instrument and improve the signal-to-noise ratio.

Figure 3 shows spectra of some slitlets in slit C. It should be noted that the slopes of the continuum at \( \lambda < 3.0 \mu m \) and \( \lambda > 3.9 \mu m \) are sensitive to the atmospheric conditions during the observation. In the following analysis, we did not use the data in these wavelength ranges to avoid the uncertainty of the continuum slope. The periodic feature at 3.46–3.56 \( \mu m \) in the spectrum of the central peak in Figure 3 is from the periodic telluric absorption in this wavelength range. Because the instrumental line profile changes with the spatial distribution of the illumination within the slit, the difference of the instrumental line profiles of the target and the standard star causes the residual features when the two spectra are divided by each other (see the detailed discussion in Goto 2005).

\(^{2}\) IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

3.3. The 3.4 \( \mu m \) Absorption Feature and the \( L \)-Band Continuum

The absorption feature around 3.4 \( \mu m \) of carbonaceous dust is clearly seen in the spectra in Figure 3. Following Sandford et al. (1991), the optical depth of the dust feature \( \tau_{3.4} \) was measured as follows: (1) the continuum level at the absorption feature was estimated by connecting the continuum levels at rest wavelengths 3.23 and 3.64 \( \mu m \) with a straight line, and (2) \( \tau_{3.4} \) was derived by averaging the optical depths at two subpeaks of the dust feature at rest wavelengths 3.38 \( \mu m \) (2955 cm\(^{-1}\)) and 3.42 \( \mu m \) (2925 cm\(^{-1}\)). The 3.48 \( \mu m \) (2870 cm\(^{-1}\)) subpeak was not included in the measurements because of the residual telluric feature described in § 3.2. Figure 4 shows the spatial change of \( \tau_{3.4} \), along with \( \tau_{9.7} \) and \( \tau_{10.4} \).

The color temperature \( T_{\text{cont}} \) and emissivity \( \varepsilon_{\text{cont}} \) in the \( L \) band were estimated by fitting a graybody model,

\[
F_{\lambda}(\lambda) = \varepsilon_{\text{cont}} \left( \frac{\lambda}{10 \mu m} \right)^{-n} B_{\lambda}(T_{\text{cont}}, \lambda),
\]

to the spectra at 3.00–3.23 and 3.64–3.90 \( \mu m \). These wavelength ranges were chosen to avoid the 3.4 \( \mu m \) dust feature and the unstable continuum level at the both ends of the wavelength range due to changes of the atmospheric conditions. We assumed a dust emissivity index of \( n = 1.6 \) for comparison of the parameters with those in the MIR (§ 2.3). The spatial change of the color temperature in the \( L \) band along with those in MIR are shown in Figure 5.
Fig. 4.— Spatial variation of optical depths of the dust features for three slit positions. Open circles, filled circles, and gray filled squares show \( \tau_{3.4} \), \( \tau_{9.7} \), and \( \tau_{10.4} \), respectively. Positive values of \( \tau \) mean absorption, while negative values mean emission. Error bars show the 1 \( \sigma \) uncertainty. Error bars for \( \tau_{10.4} \), which are similar to those for \( \tau_{9.7} \), are not shown. The vertical line at bottom left shows the spatial resolution (FWHM) of the data.

Fig. 5.— Color temperatures of the continua in the L band (open circles and upper abscissa) and in the MIR (filled circles and lower abscissa) on the three slit positions. Error bars show the 1 \( \sigma \) uncertainty of each measurement, which is less than the size of the symbols for the L-band measurements. The vertical line at the bottom left shows the spatial resolution (FWHM) of the data.
4. RESULTS AND DISCUSSION

4.1. Emission Mechanisms of MIR and L-Band Continua

Continua are detected both in the MIR and in the L band over a region of 100 pc to the north and to the south of the central engine. Because Gratadour et al. (2003) detected no evidence of stellar activity in the vicinity of the central engine in their \( K \) band spectra, stellar activity should be negligible as a source of the extended IR continua. In the following, we show that the MIR continuum is emitted from dust in thermal equilibrium with the UV radiation from the central engine, while the continuum in the \( L \) band is emitted by very small grains (VSGs).

4.1.1. MIR Continuum Emission

Assuming a dust emissivity index \( n \) of 1.6, Cameron et al. (1993) estimated the dust temperature \( T \) in thermal equilibrium with a UV radiation field as

\[
R = 0.14 \left( \frac{L}{1.5 \times 10^{11} L_\odot} \right)^{0.5} \left( \frac{T}{1500 \text{ K}} \right)^{-2.8},
\]

where \( L \) is the luminosity of the UV source and \( R \) is the linear distance from the heating source. Figure 6 shows the color temperature \( T_{\text{cont}} \) measured in the MIR and the estimated temperature for \( L = 2.2 \times 10^{11} L_\odot \) (Telesco & Harper 1980; at luminosity distance of 15 Mpc) as a function of the distance from the central engine. The distance is assumed to be the same as the projected distance on the sky. The vertical dotted lines in the figure show the spatial resolutions of data in the MIR and in the \( L \) band, which are different because of the different wavelengths and observation conditions. Because the light from the central engine, the color temperature of which might be different from that for the extended continua, might contaminate the continua, the color temperatures measured around the central engine within the spatial resolutions are not accurate.

In Figure 6, the measured \( T_{\text{cont}} \) in the MIR scatters around the estimated equilibrium temperature. This implies that, as a whole, the MIR-emitting dust is mainly heated by the central engine and is in thermal equilibrium, as has been suggested by Galliano et al. (2005).

4.1.2. L-Band Continuum Emission

We interpret the extended \( L \)-band continuum to be emitted by VSGs among the following three possibilities. First, the continuum is not dominated by the scattered light of the continuum from the central engine. Packham et al. (1997) measured spatially resolved polarization degrees in the \( J, H, \) and \( K \) bands around the central engine and found that they are not more than 5%. Second, the \( L \)-band continuum is not emitted from dust in thermal equilibrium. As shown in Figure 6, the color temperature of the \( L \)-band continuum is higher than expected for dust in thermal equilibrium. Third, the color temperature in the \( L \) band remains roughly constant as far as 100 pc from the central engine, suggesting that hot grains emitting \( L \)-band continuum exist in this area even if their column density is not as high as those emitting MIR continuum. As Rouan et al. (2004) and Gratadour et al. (2005) suggested, the uniformity of the color temperature can be explained as emission from VSGs, which emit continuum with a color temperature higher than their equilibrium temperature due to thermal fluctuation upon absorption of UV photons (Sellgren 1984; Sellgren et al. 1985).

If the continuum is emitted by VSGs, the incident UV photon flux does not determine the color temperature but determines the brightness, or emissivity in our graybody model, of the continuum. We actually found a change of emissivity of the \( L \)-band continuum to be emitted by VSGs. Figure 7 shows the correlation between \( \varepsilon_{\text{cont}}(L \text{ band})/\varepsilon_{\text{cont}}(\text{MIR}) \) and \( T_{\text{cont}}(\text{MIR}) \). The thermal equilibrium temperature \( T_{\text{cont}}(\text{MIR}) \) should correlate with the UV photon flux. On the other hand, since \( \varepsilon_{\text{cont}} \) is proportional to the column density of dust grains emitting the continuum, \( \varepsilon_{\text{cont}}(L \text{ band})/\varepsilon_{\text{cont}}(\text{MIR}) \) gives the ratio of dust grains excited to be VSGs to those in thermal equilibrium emitting continuum in the MIR. In more detail, the energy \( F \) of UV photons absorbed by dust grains is balanced with the graybody emission with temperature \( T \) by

\[
F = \pi \int \varepsilon_{\text{cont}} \left( \frac{\lambda}{10 \mu\text{m}} \right)^{-n} B_{\lambda}(T, \lambda) d\lambda \propto \varepsilon_{\text{cont}} T^{4+n},
\]
where $\varepsilon_{\text{cont}}$ is the emissivity of the dust cloud at 10 $\mu$m. Division of the two equations for the $L$-band and MIR continua leads to the equation

$$\frac{\varepsilon_{\text{cont}}(L \ \text{band})}{\varepsilon_{\text{cont}}(\text{MIR})} = \frac{F(L \ \text{band})}{F(\text{MIR})} \left[ \frac{T_{\text{cont}}(\text{MIR})}{T_{\text{cont}}(L \ \text{band})} \right]^{4+n}. \ \ (5)$$

The solid line in Figure 7 shows the fitting result when assuming $n = 1.6$ and adjusting the factor $T_{\text{cont}}(L \ \text{band})/T_{\text{cont}}(\text{MIR})$ as a free parameter. The relation between the measured $\varepsilon_{\text{cont}}(L \ \text{band})/\varepsilon_{\text{cont}}(\text{MIR})$ and the measured $T_{\text{cont}}(\text{MIR})$ in Figure 7 roughly matches with the assumption in the range of almost 2 orders of $\varepsilon_{\text{cont}}(L \ \text{band})/\varepsilon_{\text{cont}}(\text{MIR})$. The fitted factor (651 K) and the observed $T_{\text{cont}}(L \ \text{band}) \sim 560$ K lead to $F(L \ \text{band})/F(\text{MIR}) \sim 0.43$, suggesting that VSGs absorb almost half of the UV energy that is absorbed by dust grains in thermal equilibrium. The uniformity of the ratio $F(L \ \text{band})/F(\text{MIR})$ suggests that dust in thermal equilibrium and VSGs are mixed well around the central engine.

4.2. Spectral Profile Change of the Silicate Absorption Feature

At 10 $\mu$m, the silicate absorption toward the central engine is deeper than expected from the standard silicate feature. Figure 1 compares the observed SEDs with expected spectra from the IR excess toward $\mu$ Cep (Roche & Aitken 1984). There are a number of similar wavelength shifts of the silicate feature in the literature. The interferometric spectrum by Jaffe et al. (2004) also shows a shift of the peak of the absorption feature toward longer wavelength. The silicate emission feature detected toward a type I AGN (Sturm et al. 2005) and quasars (Siebenmorgen et al. 2005) is shifted to a longer wavelength.

The spatially integrated SED in Figure 1 is consistent with the spectrum observed through the 14″ × 20″ aperture of the ISO SWS (Sturm et al. 2000), which shows the normal spectral profile of the silicate absorption feature. This suggests that the spectral profile is normal as a whole and that there is a spatial change of the profile.

To measure the optical depth of the feature without being affected by the change, we fitted the MIR SED with a graybody emission model without using the 10.4 $\mu$m image. Figure 8 shows the spatial distribution of the optical depth in the 10.4 $\mu$m filter $\tau_{10.4}$. It is measured by comparing the 10.4 $\mu$m image with the model continuum surface brightness fitted from the other images. The shape of the 10.4 $\mu$m absorption area is different from the 9.7 $\mu$m absorption area (Fig. 2b). To illustrate the difference, we compared the measured $\tau_{10.4}$ with that expected from the measured $\tau_{9.7}$ and the IR excess toward $\mu$ Cep (Roche & Aitken 1984). Figure 8b shows the excess optical depth at 10.4 $\mu$m ($\Delta \tau_{10.4}$) near the central engine and to the north-northeast.

The change of the spectral profile might be due to a change of dust properties, as suggested by Siebenmorgen et al. (2005) and Sturm et al. (2005) for type 1 AGNs and quasars. The area with large $\Delta \tau_{10.4}$ in Figure 8b coincides with the pie-shaped high-emissivity area (§ 4.4) seen in Figure 2d. This suggests that the spectral profile change of the silicate absorption feature occurs in dense regions.

4.3. Spatial Variation of 9.7 $\mu$m and 3.4 $\mu$m Absorption Features

It is known that the optical depth of the absorption feature of silicate dust and that of carbonaceous dust are proportional toward Galactic sources. Roche & Aitken (1984) showed that $A_{\nu}/\tau_{9.7} = 18.5$ toward Wolf-Rayet stars and B supergiants in our Galaxy. Pendleton et al. (1994) measured optical depths of the carbonaceous dust and concluded that $A_{\nu}/\tau_{3.4}$ is ~150 for sources in the Galactic center or ~250 for sources in the local interstellar matter (ISM). From these results, the ratio of the optical depths of the absorption features $\tau_{9.7}/\tau_{3.4}$ is ~8.1 for the sources in the Galactic center or ~13.5 for the local ISM. Toward AGNs,
$\tau_{9.7}/\tau_{3.4}$ is expected to be smaller because of the temperature gradient in the dusty torus in the line of sight (Imanishi 2000). In fact, they measured $\tau_{3.4}$ toward NGC 1068 in the 3" aperture, compared it with $\tau_{9.7}$ measured in the 4" aperture by Roche et al. (1984), and found $\tau_{9.7}/\tau_{3.4} = 4.3$. With data with a higher spatial resolution, spatial variation of the ratio might show a trace of the dusty torus.

Our results show a significant spatial variation of the ratio $\tau_{\text{silicate}}/\tau_{3.4}$ (Fig. 9), with a complexity not expected to be produced by a dusty torus. As shown in Figure 1, the 9.7 $\mu$m silicate feature is shifted toward longer wavelengths at some locations: the optical depth of the feature is deeper at 10.4 $\mu$m than at 9.7 $\mu$m ($\S$ 4.2). To minimize the influence of the wavelength shift, we defined $\tau_{\text{silicate}}$ as either $\tau_{9.7}$ or $\tau_{10.4}$, whichever has the higher absolute value. At the central peak, the ratio from our observation is between that measured by Imanishi (2000) and the Galactic values. In slit C, the ratio increases from the central peak toward the north and approaches the Galactic values. In the eastern slits, the ratio is flatter and closer to that measured by Imanishi (2000). In the south, the ratio is smaller. Figure 4 shows that the silicate feature is observed as emission in the south.

The emission of the silicate feature in the south of the central peak implies a temperature gradient in the line of sight: e.g., an optically thin layer of warm dust is present in front of the cooler continuum source. On the other hand, in the north, the change of the ratio $\tau_{\text{silicate}}/\tau_{3.4}$ may be explained either with a temperature gradient in the line of sight, i.e., warmer dust clouds are located behind cooler dust clouds, or with differences in dust composition. Spatially resolved MIR spectra are needed to disentangle the possibilities.

4.4. Pie-shaped Warm Dust Cloud

With a spatial resolution of 26 pc on the sky, the plausible dusty torus is not detected. Instead, we found a pie-shaped area of high MIR emissivity in the north up to about 50 pc from the central engine (Fig. 2d). The pie-shaped area is in the west of the radio jet. There is no other hint of a channel supplying material to the central engine in the IR images in the literature, and in this study. Therefore, we speculate that the area might be a channel that supplies material to the central engine.

The lifetime of this cloud can be estimated assuming that material falls down into the central engine through the cloud. The dust mass of the cloud is estimated at 4.6 x 10$^5$ $M_\odot$ by integrating $\epsilon_{\text{cont}}$(MIR) over the cloud where $\epsilon_{\text{cont}}$(MIR) $\geq 10^{-1.6}$ and dividing by $K_{\text{dust}}$ ($\S$ 2.3). Assuming a dust-to-gas ratio of 100 (Contini & Contini 2003), the total mass of the cloud is $\sim 4.6 \times 10^7 M_\odot$. The mass accretion rate to the central engine is estimated at 0.05 $M_\odot$ yr$^{-1}$ from a total luminosity $L \sim 2.2 \times 10^{11} L_\odot$ (Telesco & Harper 1980; at a luminosity distance of 15 Mpc) and a typical value of the mass-to-luminosity conversion efficiency of a black hole $L \sim 0.3c^2 dM/dt$ (Eardley & Press 1975). The estimated total mass and accretion rate yield a lifetime of the cloud on the order of 10$^9$ yr.

5. CONCLUSION

We observed an area of 2"8 (200 pc) around the central peak of NGC 1068 in the MIR (8.8–12.3 $\mu$m) and in the L band (3.0–3.9 $\mu$m). The shifted and added MIR images have a spatial resolution of 0"37 or a projected distance of 26 pc, while the L-band spectra are taken with a seeing-limited spatial resolution of 0"3 or 22 pc. From these data, we derived graybody parameters: color temperatures of the continua and emissivities, which are proportional to column densities of dust emitting the continua, at each spatial element. Moreover, optical depths of spectral features of silicate dust around 9.7 $\mu$m and carbonaceous dust around 3.4 $\mu$m were also derived ($\S$ 2.3 and 3.3).

The extended continua over 100 pc to the north and to the south of the central source are detected both in the MIR and in
the L band. We found that the MIR continuum is mainly emitted from dust in thermal equilibrium with radiation from the central engine, while the L-band continuum is emitted by VSGs (§ 4.1). The observed SED in the MIR suggests that the peak wavelength of the 9.7 μm silicate absorption feature is shifted to a longer wavelength at some locations (§ 4.2). The ratio of the optical depths of the silicate and carbonaceous dust features shows a complicated spatial distribution (§ 4.3). There is a pie-shaped area of enhanced MIR emissivity extending about 50 pc to the north from the central engine. The morphology of the cloud leads us to speculate that the area is a channel that feeds material into the central engine (§ 4.4).

We would like to acknowledge Miwa Goto for help in reducing the IRCS data. We would also like to thank the anonymous referee for the helpful comments that significantly improved this paper. Part of this work was performed when D. T. was at Max-Planck-Institut für extraterrestrische Physik (MPE). D. T. would like to acknowledge colleagues at MPE and Takeo Minezaki for helpful comments and inspiring discussions. Cathy Ishida and Mark Garboden helped us in preparing early versions of the manuscript. The data presented in this paper were acquired in the commissioning phase of the telescope and the instruments. We are very grateful to all the Subaru staff who committed themselves to the telescope and the instruments.

REFERENCES

Antonucci, R. 1993, ARAA, 31, 473
Antonucci, R. R. J., & Miller, J. S. 1985, ApJ, 297, 621
Bock, J. J., et al. 2000, AJ, 120, 2904
Bottinelli, L., Gouguenheim, L., Fouque, P., & Paturel, G. 1990, A&AS, 82, 391
Cameron, M., Storey, J. W. V., Rotaciac, V., Genzel, B., Verstraete, L., Drapatz, S., Siebenmorgen, R., & Lee, T. J. 1993, ApJ, 419, 136
Cohen, M., Walker, R. G., Carter, B., Hammersley, P., Kidger, M., & Noguchi, K. 1999, AJ, 117, 1864
Cohen, M., Witteborn, F. C., Walker, R. G., Bregman, J. D., & Wooden, D. H. 1995, AJ, 110, 275
Contini, M., & Contini, T. 2003, MNRAS, 342, 299
Draine, B. T. 2003, ARA&A, 41, 241
Eardley, D. M., & Press, W. H. 1975, ARA&A, 13, 381
Evans, I. N., Ford, H. C., Kinney, A. L., Antonucci, R. R. J., Armus, L., & Caganoff, S. 1991, ApJ, 369, L27
Galliano, E., Alloin, D., Granato, G. L., & Villar-Martin, M. 2003, A&A, 412, 615
Galliano, E., Pantin, E., Alloin, D., & Lagage, P. O. 2005, MNRAS, 363, L1
Gallimore, J. F., Baum, S. A., & O’Dea, C. P. 1996, ApJ, 464, 198
——. 1997, Nature, 388, 852
Gallimore, J. F., Henkel, C., Baum, S. A., Glass, I. S., Claussen, M. J., Prieto, M. A., & Von Kap-herr, A. 2001, ApJ, 556, 694
Goto, M., et al. 2005, in Science with Adaptive Optics, ed. W. Brandner & Gallimore, J. F., Henkel, C., Baum, S. A., Glass, I. S., Claussen, M. J., Prieto, M. A., & Von Kap-herr, A. 2001, ApJ, 556, 694
——. 1997, Nature, 388, 852
Gratadour, D., Clénet, Y., Rouan, D., Lai, O., & Forveille, T. 2003, A&A, 411, 335
Gratadour, D., Rouan, D., Boccaletti, A., Riaud, P., & Clénet, Y. 2005, A&A, 429, 433
Imanishi, M. 2000, MNRAS, 319, 331
Imanishi, M., Terada, H., Sugiyama, K., Motohara, K., Goto, M., & Maihara, T. 1997, PASJ, 49, 69
Jaffe, W., et al. 2004, Nature, 429, 47
Johnson, H. M., & Wright, C. D. 1983, ApJS, 53, 643
Kobayashi, N., et al. 2000, Proc. SPIE, 4008, 1056
Le Floch, E., Mirabel, I. F., Laurent, O., Charmandaris, V., Gallais, P., Sauvage, M., Vigroux, L., & Cesarsky, C. 2001, A&A, 367, 487

Lutz, D., Sturm, E., Genzel, R., Moorwood, A. F. M., Alexander, T., Netzer, H., & Sternberg, A. 2000, ApJ, 536, 697
Maiolino, R., Marconi, A., Salvati, M., Risaliti, G., Severgnini, P., Oliva, E., La Franca, F., & Vanzo, L. 2001, A&A, 365, 28
Minezaki, T., Yoshii, Y., Kobayashi, Y., Enya, K., Suganuma, M., Tomita, H., Aoki, T., & Peterson, B. A. 2004, ApJ, 600, L35
Packham, C., Young, S., Hough, J. H., Axon, D. J., & Bailey, J. A. 1997, MNRAS, 288, 375
Pendleton, Y. J., Sandford, S. A., Allamandola, L. J., Tielens, A. G. G. M., & Sellgren, K. 1994, ApJ, 437, 683
Pier, E. A., & Krolik, J. H. 1992, ApJ, 401, 99
Roche, P. F., & Aitken, D. K. 1984, MNRAS, 208, 481
Roche, P. F., Whittome, B., Aitken, D. K., & Phillips, M. M. 1984, MNRAS, 207, 35
Rothman, L. S., et al. 1998, J. Quant. Spectrosc. Radiat. Transfer, 60, 665
Rouan, D., et al. 2004, A&A, 417, L1
Sandage, A. 1973, ApJ, 183, 711
Sandford, S. A., Allamandola, L. J., Tielens, A. G. G. M., Sellgren, K., Tapia, M., & Pendleton, Y. 1991, ApJ, 371, 607
Sellgren, K. 1984, ApJ, 277, 623
Sellgren, K., Allamandola, L. J., Bregman, J. D., Werner, M. W., & Wooden, D. H. 1985, ApJ, 299, 416
Siebenmorgen, R., Haas, M., Krügel, E., & Schulz, B. 2005, A&A, 436, L5
Sturm, E., Lutz, D., Tran, D., Feuchtgruber, H., Genzel, R., Kunze, D., Moorwood, A. F. M., & Thornley, M. D. 2000, A&A, 358, 481
Sturm, E., et al. 2005, ApJ, 629, L21
Telesco, C. M., & Harper, D. A. 1980, ApJ, 235, 392
Tokunaga, A. T., et al. 1998, Proc. SPIE, 3354, 512
Tomono, D. 2000, Ph.D. thesis, Univ. Tokyo
Tomono, D., Doi, Y., & Nishimura, T. 2000, Proc. SPIE, 4008, 853
Tomono, D., Doi, Y., Usuda, T., & Nishimura, T. 2001, ApJ, 557, 637
Weingartner, J. C., & Draine, B. T. 2001, ApJ, 548, 296