1. INTRODUCTION

Massive young stellar objects are luminous, embedded infrared (IR) sources that show many signs that they are still actively accreting mass. Their luminosity \( L > 10^{4} L_{\odot} \) is such that they are expected to be ionizing their surroundings to produce an H II region, yet they only have weak radio emission due to ionized winds or jets (Hoare 2002). Most appear to be driving bipolar molecular flows, and (sub)millimeter interferometry is beginning to reveal evidence of rotating, disk-like structures on scales of hundreds of AU (Patel et al. 2005; Beltrán et al. 2006; Torrelles et al. 2007). There is great interest in knowing the distribution of the infalling and outflowing material on smaller scales; this distribution may provide clues to which physical processes are controlling the dynamics and setting the final mass of the star (Beuther et al. 2007; Hoare et al. 2007). The mid-IR (8–13 \( \mu \)m) emission from MYSOs is thought to arise in the warm \((\sim 300 \text{ K})\) dust in the envelope heated by the young star. Previous modeling (e.g., Churchwell et al. 1990) has indicated that the size of the mid-IR emission region should be unresolved at the typical distances of MYSOs by single-dish telescopes, and this is borne out by observations (Kraemer et al. 2001; Mottram et al. 2007). Exceptions occur when MYSOs are viewed close to edge-on, when a dense torus can completely obscure the bright central region and only the warm dust in the outflow cavities is seen (De Buizer 2006).

Here we present new results from mid-IR interferometric observations of the MYSO W33A, using VLTI/MIDI. W33A has a kinematic distance of 3.8 kpc and a luminosity derived from IRAS fluxes of \( 1 \times 10^{5} L_{\odot} \) (Faúndez et al. 2004). It has weak, compact, optically thick radio continuum emission (Rengarajan & Ho 1996; van der Tak & Menten 2005) and broad \((\sim 100 \text{ km s}^{-1})\), single-peaked H I recombination emission lines (Bunn et al. 1995), consistent with an ionized stellar wind origin. IR images from 2MASS and GLIMPSE clearly show a large-scale monopolar nebula emerging to the southeast, which is most likely demarcating the blueshifted lobe of a bipolar outflow.

The cold dust envelope has been studied at a few arcsecond resolution at millimeter wavelengths (van der Tak et al. 2000), probing the imprint of the star formation process on the circumstellar dust distribution. Many different scenarios have been put forward predicting this distribution. In the case of W33A, Gürtler et al. (1991) modeled the SED with a constant density spherical envelope and found an inner cavity radius of 135 AU (35 mas at 3.8 kpc), with the dust close to the sublimation temperature. MIDI provides data on comparable size scales of 50 mas, and since the mid-IR size will be somewhat larger than the sublimation zone, we expect the emission to be well resolved.

2. OBSERVATIONS AND DATA REDUCTION

MIDI is the VLTI’s two-telescope-beam combiner that operates in the thermal IR (Leinert et al. 2003). W33A was observed with MIDI on 2005 September 16, employing the UT2-UT3 configuration for a projected baseline of 45.5 m and a position angle of 47° east of north; this is perpendicular to the star’s outflow direction. An interferometric calibrator star, HD 169916, was observed during the same night. Lunar occultation and indirect methods reveal the calibrator diameter to be a few milliarcseconds (Nather 1972; Pasinetti Fracassini et al. 2001), too small to be resolved by MIDI. Here we present visibilities between 8 and 13 \( \mu \)m that are spectrally dispersed at a resolution of \( R = 30 \). The observations were executed in the High-Sens MIDI mode (for details, see Przygodda et al. 2003, Chesnay et al. 2005, and Leinert et al. 2004). We summarize the main elements of the procedure that produces the raw data set. The two beams are combined to produce two complementary interferometric channels that have a phase difference of \( \pi \) radians. The dispersed fringes are modulated according to the introduction of an optical path delay (OPD). Interferograms are recorded for a range of OPDs—a few millimeters around optical path length equalization—which is called a fringe scan. For both
W33A and HD 169916, a total of 8000 interferograms, corresponding to 200 scans, were recorded. Subtracting the two interferometric beams eliminates the background and enhances the fringe signal. The coherent flux was extracted using two different MIDI software reduction packages: EWS (Jaffe 2004) and MIA (Köhler 2005). MIA estimates the amplitudes in the power spectra of the fringe signal Fourier transform (incoherent estimation). The amplitudes are proportional to the correlated flux. EWS, on the other hand, aims at adding the fringes to maximize the signal-to-noise ratio (S/N; coherent estimation). This method corrects the fringe spectra for their corrupted phase, which is caused by atmospheric and instrumental effects. EWS uses the fringe scan as a phase reference, to estimate the group delay due to the atmosphere. The observations show that the atmospheric group delay varied within a range of 50 μm over 100 s, indicating relatively good atmospheric circumstances during the night. The Fourier transform of the group delay function reveals the typical sawtooth-phase change due to the introduction of an OPD, indicating that fringes have been measured. Removing the atmospheric and the (known) instrumental group delays constitutes a linear correction to the dispersed fringe signal and straightens the dispersed fringe spectra (i.e., the phase is independent of wavelength). Next, the phase offset due to varying the water-refraction index between the time of recording of the fringe spectra has to be accounted for. In principle, all spectra can then be added to a final fringe spectrum. Final visibilities are obtained by taking two spectra of the source (one with each telescope) immediately after the interferometric measurement. The accuracy of the final visibility spectrum is limited by the sky brightness variation between the interferometric and flux measurements and can amount to a 10%–15% variation.

The flux spectra are corrected for sky contribution by using a median sky subtraction. Spectra are extracted by summing the counts within 3 σ of the mean position, determined from a Gaussian fit to each column along the wavelength axis. This procedure results in a W33A spectrum with S/N ~ 100 (S/N ~ 300 for the standard star). Four spectra are recorded, two for each telescope beam, and combined via a geometric mean. This quantity is also what is obtained for the correlated flux after beam combination and thus ensures consistency when deriving visibilities. The absolute flux calibration is done using HD 169916, which has an average flux density of 30 Jy between 8 and 13 μm (Cohen et al. 1999). The difference in air mass between the observation of the flux calibrator and W33A is 0.05, leading to a negligible correction on the final fluxes. Error bars on the spectrum in Figure 1 indicate the systematic difference in flux levels between the two telescopes beams. Absolute flux calibration is uncertain up to at least 35%, due to the differences in the flux level of HD 169916 in each telescope beam.

3. RESULTS

Figure 1 presents the MIDI total flux spectrum and correlated flux spectrum from EWS and MIA. The flux spectrum is compared to the ISO-SWS spectrum, taken from the ISO Data Archive maintained by ESA. Both spectra are dominated by a very strong silicate feature that contains solid-state ammonia and methanol absorption features, at 9 and 9.7 μm, respectively (see Gibb et al. 2000). At the central wavelength of the feature, no flux was recorded, and the actual depth is unknown. The MIDI and ISO spectra exhibit a similar overall shape, but the MIDI spectrum has a flux level that is about a factor 2 less. In addition to the uncertainties due to flux calibration, we ascribe this difference to the much larger ISO-SWS beam (20”) in comparison to the MIDI slit width (0.5”).

The corresponding visibility spectrum is obtained by dividing the correlated flux by the flux spectrum and is presented in the left panel of Figure 2. Visibilities are not plotted when they correspond to correlated fluxes smaller than 0.1 Jy, a value below which the measurements become unreliable (Jaffe 2004; Matsuura et al. 2006). The visibility spectrum shows that the silicate wings are not strongly affected by the decrease in flux but instead follow the declining trend of the continuum visibilities. If we represented the emission by a Gaussian-emitting distribution, then the FWHM size would increase from 30 mas at 8 μm to 60 mas at 13 μm.

4. RADIATIVE TRANSFER MODELING

Previous model fits of MYSO SEDs have indicated that simple spherical radiative transfer models with roughly constant densities best fit the near-IR and far-IR data (Churchwell et al. 1990; Gürtler et al. 1991). However, evidence shows that the outer envelopes (10,000 AU scales) have steeper density pro-
files (Hoare 1990; van der Tak et al. 2000). We explore here whether the visibilities produced by material on 100 AU scales (scales previously unexplored) and the SED can be simultaneously matched by simple 1D spherically symmetric dust models. Arguably, such models are inadequate for MYSOs, which are likely to consist of circumstellar disks, bipolar cavities, etc. Despite this, we explore whether the basic levels and trends of the dispersed visibilities can be matched by a single unresolved star deeply embedded in a dusty envelope, before introducing more free parameters.

For this purpose, we employ DUSTY, a code that solves the scaled 1D dust radiative transfer problem (see Ivezić & Elitzur 1997). We used a spherically symmetric dust distribution illuminated by a central, unresolved star. The only nonscaled parameter entering the code is the dust sublimation temperature. Gas emission is not taken into account by DUSTY. Solutions are independent of the central source luminosity, and the SED and visibilities can be scaled accordingly. The luminosity is the prime stellar parameter that sets the inner dust sublimation radius and thus the size scale; an increase causes the size of the prime stellar parameter that sets the inner dust sublimation and visibilities can be scaled accordingly. The luminosity is the parameter entering the code is the dust sublimation temperature. luminated by a central, unresolved star. The only nonscaled challenge is to construct a single model that fits the observed visibilities, silicate wings, and mid-IR SED up to 100 \( \mu \)m. We restrict the SED fitting to this wavelength interval, as it is well known that it is particularly difficult for 1D models to reproduce the short-wavelength region because of the sensitivity to the viewing angle (e.g., Yorke & Sonnhalter 2002).

We adopt a dust sublimation temperature of 1500 K and an MRN-DL dust mixture (Mathis et al. 1977; Draine & Lee 1984) with a typical interstellar graphite-silicate composition. The outer bound of the model is set at 1000 times the dust sublimation radius, where the temperature corresponds to the presumed ambient temperature of the ISM, between 10 and 25 K. The precise value for the outer radius does not affect our conclusions here.

Previous studies have shown that W33A is best described by an \( A_v \) between 100 and 200 (Capps et al. 1978; Güttler et al. 1991). A first result is that the MIDI visibilities cannot be reproduced for any density distributions with power exponents between \(-2.0\) and 0.0 for \( A_v \) between 100 and 200, and \( L = 1 \times 10^5 L_{\odot} \). The model visibilities at 10 \( \mu \)m are too small by an order of magnitude. Decreasing \( A_v \) is not a solution for normal dust, because of W33A’s exceptionally strong silicate absorption feature. Average model sizes at 10 \( \mu \)m of \( \sim 200 \) AU are reached only if the luminosity is reduced to about a third. Such a reduction is justified when we consider 70 \( \mu \)m MIPS-GAL data that we have obtained from the Spitzer archive. These data are taken at a vastly superior resolution, compared to both IRAS and ISO, and reveal the presence of at least three point sources and strong diffuse emission within the IRAS beam. For W33A, we measure a 70 \( \mu \)m flux of \( 1.1 \times 10^{3} \) Jy (20% uncertainty), as shown in Figure 2. This indicates that the true luminosity is significantly less than deduced from IRAS data.

Even with the luminosity reduced to \( 4 \times 10^4 L_{\odot} \), thermally supported cores with \( r^{-2} \) dependency (Larson 1969) are incompatible with the observed trend of decreasing visibilities with wavelength and the SED. Incompatible models are also found if we adopt a constant infall velocity–type distribution with \( r^{-1.5} \) (Shu 1977). Reasonable fits to the SED that produce sizes comparable to the MIDI visibilities are found for \( r^{-1.6} \) logatropic distributions (e.g., McLaughlin & Pudritz 1996), but again they do not reproduce the observed decreasing visibility trend with wavelength. DUSTY produces smaller sizes, and thus larger visibilities, for longer wavelengths. This affects especially the red wing of the silicate feature, due to the diminishing opacity farther out in the silicate wing. However, this mismatch in visibilities is removed if we reduce the slope to a much shallower density distribution with a \( r^{-0.5} \) law or a constant density law. These distributions fit the short-wavelength region of the SED increasingly less because of the loss of warm dust. These shallower density distributions also require the luminosity of the central object to be fainter than observed. We thus find that for standard...
ISM dust, the SED and the sizes at scales of 100 AU limit the dust to follow distributions between $r^{-1.0}$ and $r^{-0.5}$ power laws. The required optical depths are relatively high, yet the best models do not fit the SED particularly well.

Different dust compositions influence both the magnitude and the shape of the visibility spectrum. We now explore dust made of cold and warm silicates (Ossenkopf et al. 1992) and amorphous carbon. Ossenkopf et al. silicates have the strong advantage of a larger optical depth in the silicate feature than that in the DL grains. This property is advantageous in the case of W33A, because it allows models with relatively moderate $A_V$ to produce deep silicate absorption. Models with moderate extinction fit the shorter wavelength fluxes better. We find that the typical ISM ratio of 0.88 between graphite and silicates does not produce enough silicate absorption to fit W33A’s strong absorption feature. A better correspondence is reached if this ratio is reduced to 0.50 (see also Churchwell et al. 1990). The warm Ossenkopf et al. silicates have the extra advantage of somewhat reducing the sublimation radius. Although the reduction in $A_V$ and a better correspondence to the silicate feature depth produce reasonable correspondence between the shallow density models with the observation, models that fit the data better are found by lowering the $T_{\text{eff}}$ of the star. The change in this parameter produces a decrease in the size of the inner dust boundary, because of the lower dust opacity with temperature. We finally arrive at a simultaneous fit (Fig. 2) to the red silicate wing, an SED peak, and visibilities for a central object with a relatively low $T_{\text{eff}}$ of 10$^4$ K (corresponding to a B9 supergiant, again consistent with the notion that an accreting star may be swollen) and a $r^{-0.5}$ density law (Fig. 2). The dust sublimation radius for $T_{\text{eff}} = 1500$ K is found at 7 mas (26.5 AU).

In summary, fitting 1D DUSTY models to the visibilities and SED of W33A has shown that for nominal stellar parameters, size scales of the emission region are too large and produce the wrong trend with wavelength. Shallow radial density distributions produce this trend of size with wavelength, and, in order to fit the depth of the silicate feature as well, dust models with warm Ossenkopf et al. silicates (with an increased silicate-to-graphite ratio) reproduce the observation best, provided the luminosity and $T_{\text{eff}}$ of the central object are reduced.

5. CONCLUSIONS

We presented mid-IR high-resolution dispersed interferometric observations of the forming massive star W33A. The visibility spectrum indicates an equivalent Gaussian FWHM of the emitting region of $\sim 120$ AU, at 8 $\mu$m, increasing to $\sim 240$ AU, at 13 $\mu$m. We interpreted the interferometric data with simple spherically symmetric DUSTY models representative of a (unresolved) star embedded in a dusty envelope, aiming for a simultaneous fit to the SED, the silicate profile, and the visibility spectrum. For any radial dust distribution, we found that the canonical value of W33A’s luminosity is not compatible with the visibilities. This is supported by MIPSGAL data. We found that even for a reduced luminosity, the model produces emitting regions that are too large, thus causing the visibilities and SED to be mutually incompatible. Changing the dust composition improves the situation for an increased graphite-to-silicate ratio, using warm silicate optical constants from Ossenkopf et al. (1992). We resorted to a substantial lowering of the $T_{\text{eff}}$ in order to obtain a satisfactorily match between observables and models. Further coverage of the $(u, v)$-plane will be very rewarding, constraining more appropriate, higher dimensionality models, which will eventually lead to a proper description of the circumstellar environment of an accreting massive star. A full 2D axisymmetric treatment of this and other MIDI data will be the subject of a future paper.

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