High-resolution near-infrared speckle interferometry and radiative transfer modeling of the OH/IR star OH 104.9+2.4

D. Riechers [(1),(2)], Y. Y. Balega [(3)], T. Driebe [(1)], K.-H. Hofmann [(1)], A. B. Men'shchikov [(1),(4)], D. Schertl [(1)], and G. Weigelt [(1)]

(1) Max-Planck-Institut für Radioastronomie, Bonn, Germany

(2) Max-Planck-Institut für Astronomie, Heidelberg, Germany

(3) Special Astrophysical Observatory, Nizhnij Arkhyz, Karachaevo-Cherkesia, Russia

(4) Institute for Computational Astrophysics, Saint Mary's University, Halifax, Canada

MAX-PLANCK-GESELLSCHAFT

Abstract

We present near-infrared speckle interferometry of the OH/IR star OH 104.9+2.4 in the K' band obtained with the 6 m telescope of the Special Astrophysical Observatory (SAO). At a wavelength of $\lambda = 2.12\,\mu$m the diffraction-limited resolution of 74 mas was attained. The reconstructed visibility reveals a spherically symmetric, circumstellar dust shell (CDS) surrounding the central star. The visibility function shows that the stellar contribution to the total flux at $\lambda = 2.12\,\mu$m is less than $\sim$50%, indicating a rather large optical depth of the CDS. The azimuthally averaged 1-dimensional Gaussian visibility fit yields a diameter of 47 ± 3 mas (FWHM), which corresponds to 112 ± 13 AU for an adopted distance of $D = 2.38 \pm 0.24$ kpc. To determine the structure and the properties of the CDS of OH 104.9+2.4, radiative transfer calculations using the code DUSTY were performed to simultaneously model its visibility and the spectral energy distribution (SED). We found that both the ISO spectrum and the visibility of OH 104.9+2.4 can be well reproduced by a radiative transfer model with an effective temperature $T_{\rm eff} = 2500 \pm 500$ K of the central source, a dust temperature $T_{\rm in} = 1000 \pm 200$ K at the inner shell boundary $R_{\rm in} \simeq 9.1\,R_* = 25.4$ AU, an optical depth $\tau_{2.2\mu{\rm m}} = 6.5 \pm 0.3$, and dust grain radii ranging from $a_{\rm min} = 0.005 \pm 0.003\,\mu$m to $a_{\rm max} = 0.2 \pm 0.02\,\mu$m with a power law $n(a) \propto a^{-3.5}$. It was found that even minor changes in $a_{\rm max}$ have a major impact on both the slope and the curvature of the visibility function, while the SED shows only minor changes. Our analysis demonstrates the potential of dust shell modeling constrained by both the SED and visibilities.

Introduction

OH/IR stars are long-period variables (pulsation periods between 500 and 3000 d) of variability type Me, similar to long-period Mira stars. While the majority of these stars show a bolometric amplitude of typically $\sim 1^{\rm m}$ a very small fraction varies irregularly with a low amplitude or does not show any detectable variability. OH/IR stars are mostly low and intermediate mass (progenitor masses $M \leq 9\,M_\odot$), oxygen-rich single stars evolving along the upper part of the asymptotic giant branch (AGB). Thus, they stars extend the sequence of optical Mira variables towards longer periods, larger optical depths and higher mass-loss rates. As a consequence of their high mass loss, OH/IR stars are surrounded by massive, optically and geometrically thick circumstellar envelopes composed of gas and dust. OH 104.9+2.4 is an OH/IR type II-A class star. These objects exhibit the maximum of their SED in the infrared (IR) around 6-10 μm, while the 9.7 μm silicate feature is found to be in absorption.

Observations

Figure 1: The Russian SAO 6 m telescope.

The two main input parameters for our calculations are the visibility and the SED, which are modeled simultaneously. The data for the visibility construction was obtained using the SAO 6 m telescope on Sep 22, 2002 by applying the speckle interferometry method [1]. The measurements were accomplished with a K'-band filter at $\lambda = 2.12\,\mu$m ($FWHM = 0.11\,\mu$m). Recent spectro-photometric K-band data imply that our measurements were carried out near the maximum pulsation phase of OH 104.9+2.4.

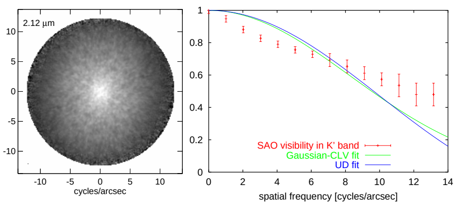
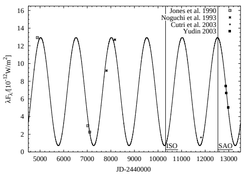


Figure 2: Observations of OH 104.9+2.4 on Sep 22, 2002 at the SAO. **Left**: 2-D visibility. **Right**: Azimuthally averaged visibility in the K' band. The visibility is fitted with a Gaussian center-to-limb variation (CLV) [$d_{\rm gauss} = 47 \pm 3$ mas, blue] and a uniform-disc (UD) [$d_{\rm UD} = 73 \pm 5$ mas, green] model as a first, rough estimate for the diameter of the CDS.

OH 104.9+2.4 is a long-period variable ($P = 1500 \pm 11$ d) with a distance of $D = 2.38 \pm 0.24$ kpc obtained with the MASER phase lag method [2]. The bolometric flux was derived from the 1996 ISO SED data ($F_{\rm bol} = 6.99 \cdot 10^{-11}$ W/m^2) and found to be near minimum phase (a slightly lower value than given in [3]). It turns out that $F_{\rm bol}$ varies by a factor of at least 3.3 within a full pulsation cycle. The total luminosity was determined to be $L = 1.23 \pm 0.12 \cdot 10^4\,L_\odot$, leading to a stellar radius of $R = 600\,R_\odot$. The mass was derived to be $M \approx 1\,M_\odot$ with an estimated mass loss rate of $\dot{M} \simeq 2.2 \cdot 10^{-5}\,M_\odot$/yr (calculation made using the method described in [3]).

Figure 3: Pulsation period at $\lambda = 2.2\,\mu$m utilizing measurements from [4-7], together with a cosine fit which delivered $P = 1500 \pm 11$ d. The left and right vertical lines indicate the date of the ISO SED (left, $\Phi_{\rm ISO} = 0.5$) and the SAO visibility measurements (right, $\Phi_{\rm SAO} = 0$). Due to the phase difference between both measurements, the bolometric flux at $\Phi_{\rm SAO}$ is higher by a factor of $\sim$ 3.3 than at $\Phi_{\rm ISO}$.



Radiative Transfer Modeling

Our goal was to simultaneously model the visibility and the SED of OH 104.9+2.4. To accomplish this, we used the 1-D radiative transfer code DUSTY [8] to scan large fractions of the corresponding parameter space. Several 10^5 models were calculated. DUSTY utilizes the IR signature of the dusty medium to analyze the structure of the optically obscured object. The obscuration is caused by dust scattering, absorption, and re-emission of the originating radiation. In the case of spherical symmetry, the equation of radiative transfer is invariant concerning all scales of density and distance. This can be formulated explicitly by substituting those parameters by dimensionless quantities. Therefore, we obtain self-similar solutions to the radiative transfer problem that being parameterized only by the bolometric flux and luminosity of a specific object. This fact allows DUSTY to solve a self-consistent radiative energy density equation with very few input parameters. These are the spectral shape $f_\mu = F_\mu/F_{\rm bol}$, of the central source, general dust absorption properties and scattering cross sections, the dust density profile, and an optical depth τ_μ at a reference wavelength μ. As the code does not correct for interstellar reddening, we added a routine to do this. DUSTY delivers reliable output for a wide range of optical depths, being the main parameter.

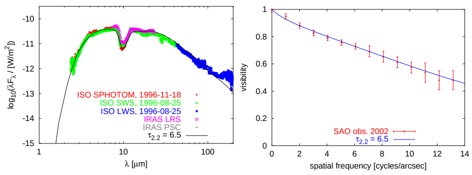


Figure 4: SED (**left**) and visibility (**right**) of OH 104.9+2.4 for our best-fitting model. The bolometric flux used for the SED is a factor of 3.3 lower than the one used for the visibility, in order to take into account the different epochs of the ISO and SAO observations.

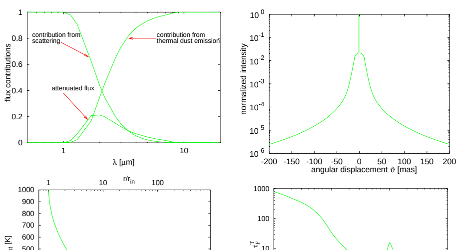


Figure 5: Modeling results of OH 104.9+2.4 for our best-fitting model. **Top left**: Fractional contributions to the total flux. The contribution from direct stellar light is small in comparison to the contribution of the processes in the CDS. **Top right**: The normalized intensity profile at 2.12 μm. The sharp central peak corresponds to the central source of radiation. **Bottom left**: Dust temperature as a function of angular distance (lower axis) and of the distance in units of the inner dust shell radius (upper axis). The point where $T_{\rm dust} = 1000$ K indicates the inner radius of the dust shell ($\frac{r}{r_{\rm in}} = 1$). **Bottom right**: Wavelength depencence of the total optical depth.

The best model obtained with DUSTY is the one shown in Figure 3 with $\tau_{2.2\mu{\rm m}} = 6.5$. While producing reasonable dust properties, it enables us to verify observational properties such as D, $F_{\rm bol}$, L, M, and R and derive quantities such as $\dot{M} \simeq 2.2 \cdot 10^{-5}\,M_\odot$/yr which is in agreement with the value given in [2]. In addition, the inner radius of the optically thick dust shell was found to be $\vartheta = 10.5$ mas, corresponding to 9.1 stellar radii. The model parameters of our best-fitting model are summarized in Table 1.

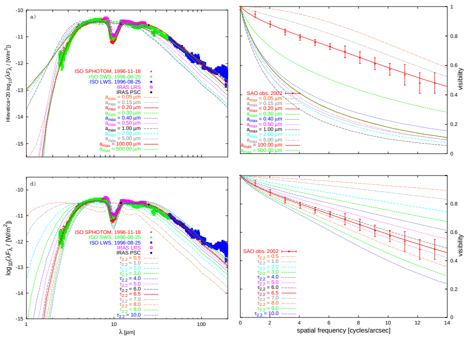


Figure 6: Illustration of the model parameter variation. Exemplarily shown are the impact on SED (**left**) and K-band visibility (**right**) of OH 104.9+2.4 when varying the maximum grain size (upper panels, see labels for parameter values) and the optical depth at $\lambda = 2.2\,\mu$m (lower panels). Our best-fitting model is indicated by the thick solid red line.

Parameter	Value
Effective temperature (black-body)	$T_{\rm eff} = 2500 \pm 500$ K
Temperature at inner CDS boundary	$T_{\rm in} = 1000 \pm 200$ K
Density profile within the CDS	$\rho(r) \propto r^{-n}$ with $n = 2.0 \pm 0.1$
Relative CDS thickness	$\frac{r_{\rm out}}{r_{\rm in}} = 10^p$ with $p = 5^{+\infty}_{-2}$
Dust grain distribution function	MRN [9]
Minimum grain size	$a_{\rm min} = 0.005 \pm 0.003\,\mu$m
Maximum grain size	$a_{\rm max} = 0.2 \pm 0.02\,\mu$m
Dust types	95 % OHM warm silicates [10]
	5 % DL astronomical silicates [11]
Optical depth	$\tau_{0.55\,\mu{\rm m}} = 158 \pm 7$
	$\tau_{2.2\,\mu{\rm m}} = 6.5 \pm 0.3$
	$\tau_{9.7\,\mu{\rm m}} = 14.0 \pm 0.6$
Radius	$R_\star \simeq 600\,R_\odot = 2.79$ AU
Radius of inner CDS boundary	$R_{\rm in} = 9.1\,R_\star = 25.4$ AU
Mass-loss rate	$\dot{M} = 2.2 \cdot 10^{-5}\,M_\odot$/yr

Table 1: Physical parameters of OH 104.9+2.4 from our best-fitting model.

Conclusions

- OH 104.9+2.4 was measured in the K' band with a diffraction-limited resolution of 74 mas at the Russian SAO 6 m telescope using the speckle interferometry technique with very high precision. No deviation from spherical symmetry was found.
- The visibility and the SED were simultaneously modeled with the radiative transfer code DUSTY.
- According to our best models, OH 104.9+2.4 is surrounded by an optically thick ($\tau = 6.5 \pm 0.3$ at $\lambda = 2.2\mu$m), spherically symmetric dust shell with an inner radius of $\vartheta = 10.5$ mas, corresponding to 9.1 stellar radii. The mass loss rate was determined to be $\dot{M} \simeq 2.2 \cdot 10^{-5}\,M_\odot$/yr, which is in accordance with observations.
- A more detailed discussion on the topics presented here is given in [12].

References

[1] Labeyrie, A. 1970, *A&A* **6**, 85
[2] Herman, J., Habing, H. J. 1985, *Astr. Astrophys. Suppl. Ser.* **59**, 523
[3] Ivezic, Z., Elitzur, M. 1995, *ApJ* **445**, 415
[4] Jones, T. J., Bryja, C. O., Gehrz, R.D. et al. 1990, *Astrophys. J.-Suppl. Ser.* **74**, 785
[5] Noguchi, K., Qian, Z., Wang, G., Wang, J. 1993, *Publ. Astr. Soc. Japan* **45**, 65
[6] Cutri, R. M., Skrutskie, M. F., van Dyk, S. et al. 2003, *VizieR ODC 2246*
[7] Yudin, B. 2003, private communication
[8] Ivezic, Z., Nenkova, M., Elitzur, M. 1999, *Internal Report, Univ. of Kentucky*
[9] Mathis, J. S., Rumpl, W., Nordsieck, K. H. 1977, *ApJ* **217**, 425
[10] Ossenkopf, V., Henning, Th., Mathis, J. S. 1992, *A&A* **261**, 567
[11] Draine, B. T., Lee, H. M. 1984, *ApJ* **285**, 89
[12] Riechers, D., Balega, Y. Y., Driebe, T., Hofmann, K.-H., Schertl, D., Men'shchikov, A. B., Weigelt, G. 2004, *A&A* , accepted

Poster presented at the *SPIE conference on New Frontiers in Stellar Interferometry,*
21st-25th June 2004, Glasgow, Scotland
contact e-mail: riechers@mpia.de