The Circumstellar Environment of Evolved Stars as seen by VLTI/MIDI

K. Ohnaka[1], J. Bergeat[2], T. Driebe[1], U. Graser[3], K.-H. Hofmann[1], R. Köhler[3], Ch. Leinert[3], B. Lopez[4], F. Malbet[5], S. Morel[6], F. Paresce[7], G. Perrin[8], Th. Preibisch[1], A. Richichi[7], D. Schertl[1], M. Schöller[6], H. Sol[8], G. Weigelt[1], and M. Wittkowski[7]

[1] Max-Planck-Institut für Radioastronomie, Bonn, Germany
kohnaka@mpifr-bonn.mpg.de
[2] Observatoire de Lyon, St.-Genis-Laval, France
[3] Max-Planck-Institut für Astronomie, Heidelberg, Germany
[4] Observatoire de la Côte d'Azur, Nice, France
[5] Laboratoire d'Astrophysique, Observatoire de Grenoble, Grenoble, France
[6] European Southern Observatory, Santiago, Chile
[7] European Southern Observatory, Garching, Germany
[8] Observatoire de Paris-Meudon, Meudon, France

Summary. We present the results of the first mid-infrared interferometric observations of the Mira variable RR Sco with the VLTI/MIDI, together with K-band observations using VLTI/VINCI. The uniform-disk diameter was found to be 18 mas between 8 and 10 μm, while it gradually increases at wavelengths longer than 10 μm to reach 24 mas at 13 μm. These uniform-disk diameters in the mid-infrared are significantly larger than the K-band uniform-disk diameter of 10.2 ± 0.5 mas measured using VLTI/VINCI, three weeks after the MIDI observations. Our model calculations show that optically thick emission from a warm molecular envelope consisting of H_2O and SiO can cause the apparent mid-infrared diameter to be much larger than the continuum diameter, and this can explain the mid-infrared angular sizes roughly twice as large as that measured in the K band. The observed increase of the uniform-disk diameter longward of 10 μm can be explained by an optically thin dust shell consisting of corundum and silicate grains.

1 Introduction

Mass loss in asymptotic giant branch (AGB) stars is believed to play an important role in the chemical evolution of the Galaxy, since nuclear processed material is dredged up to the surface and finally returned to the interstellar space via mass loss. However, the mass loss mechanism in AGB stars is not yet fully understood. In particular, the understanding of the region where material is accelerated is meager. In order to better understand the mass loss phenomenon in Mira-type AGB stars, it is crucial to obtain a comprehensive picture of the region where mass outflows are expected to be initiated, that is, the region between the top of the photosphere and the inner edge of the expanding dust shell. Mid-infrared interferometry provides a unique opportunity to probe the circumstellar environment of Mira variables. Since a large

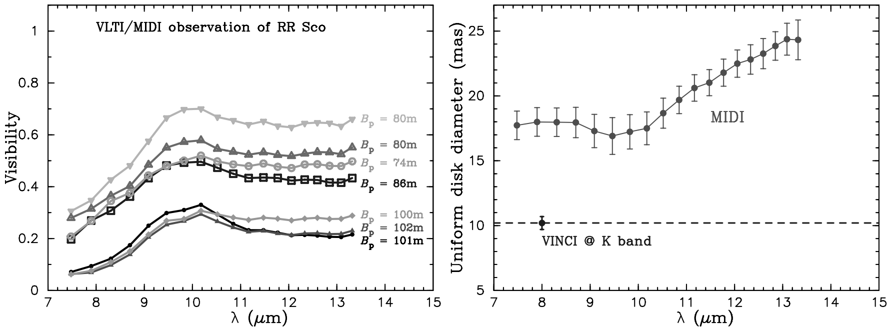

Fig. 1. Left: Visibility as a function of wavelength for different projected baseline lengths ranging from 74 m to 102 m. All curves show a similar shape: a gradually increasing part shortward of 10 μm and a roughly constant part longward of 10 μm. The errors of the calibrated visibilities are typically 10–15%, but the error bars are omitted in this panel for the sake of clarity. **Right:** Uniform-disk diameter as a function of wavelength. The diameters are derived from uniform-disk fits using all seven visibility points at each wavelength. The K-band uniform-disk diameter measured with VINCI is also plotted.

fraction of mid-infrared photons originate in regions cooler than the photosphere, mid-infrared interferometry is well suited for studying the outer atmosphere and the circumstellar dust shell, where complicated, mutually coupled physical and chemical processes take place, finally leading to the onset of mass outflows.

The MIDI instrument at VLTI has a particularly great potential with its spectro-interferometric capability, which enables us to directly observe the spatial structures of molecular and dust formation regions. We present the first spectrally dispersed N-band interferometric observations of the Mira variable RR Sco with VLTI/MIDI and, in addition, K-broadband observations with VLTI/VINCI.

2 MIDI and VINCI observations

RR Sco was observed with MIDI at variability phase 0.6 on three consecutive nights in June 2003 within the framework of the Science Demonstration Time (SDT) program. A prism with a spectral resolution of $\lambda/\Delta\lambda \simeq 30$ was used to obtain spectrally dispersed fringes. In total, seven observations were carried out using the 102 m baseline between the telescopes UT1 and UT3. Due to projection effects, the projected baseline lengths range between 74 and 102 m. For the data reduction, we used the MIDI software package based on the power spectrum analysis (Leinert et al. [4]). The calibrated visibilities of RR Sco are plotted in Fig. 1a. We also fitted all seven visibility points at each wavelength with a uniform disk and the derived uniform-disk diameters are plotted in Fig. 1b as a function of wavelength.

In addition to the MIDI measurements, we used a total of five K-band VLTI/VINCI observations of RR Sco which are publicly available in the ESO archive. These VINCI observations were carried out on 2003 July 10 and 2003 July 11, roughly three weeks after the MIDI SDT observations. The two VLTI siderostats on stations E0 and G0 were used, forming a baseline length of 16 m. We fitted the observed visibility points with a uniform disk, as described in Wittkowski et al. [10]. The fit results in a uniform-disk diameter $d_{\mathrm{UD}} = 10.2 \pm 0.5$ mas which is significantly smaller than the diameters derived with MIDI in the mid-infrared (see Fig. 1b).

3 Modeling of the observed *N*-band and *K*-band visibilities

In the present work, we attempt to interpret the observed visibility using a simple model of the warm molecular envelope and an optically thin dust shell. We approximate the star with a blackbody of 3000 K and a radius $R_\star$. The star is surrounded by a warm molecular envelope consisting of H_2O and SiO gas with a constant temperature and density, extending to R_{mol}. The inner radius of the molecular envelope is set to be equal to $R_\star$. The input parameters of our model are the outer radius and the temperature of the molecular envelope (R_{mol} and T_{mol}, respectively) as well as the column densities of H_2O and SiO ($N_{\mathrm{H_2O}}$ and N_{SiO}, respectively) in the radial direction.

We estimate the stellar radius $R_\star$ from the K-band uniform-disk diameter measured with VINCI. The analysis of VINCI data on the prototypical Mira o Cet by Woodruff et al. [11] shows that the uniform-disk diameter of o Cet at phase 0.4 is 33.3 mas, while the continuum diameter at 1.04 μm at the same phase is 29.5 mas, which is 13% smaller than the uniform-disk diameter. We apply this conversion factor to the K-band uniform-disk diameter of 10.2 mas obtained with VINCI. This results in a 1.04 μm continuum diameter of 9.0 mas, which corresponds to a radius of 4.5 mas. We adopt this 1.04 μm continuum radius as the angular radius corresponding to the stellar radius $R_\star$.

We first calculate the line opacity due to H_2O and SiO in the wavelength range between 8 and 13 μm. We adopt a Gaussian line profile with a FWHM of 5 km s^{-1}, which represents the thermal and (micro-)turbulent velocities in the atmosphere of RR Sco, and assume that the molecular gas is in local thermodynamical equilibrium. The line list of H_2O was taken from the HITEMP database (Rothman [8]), while the line list of the fundamental bands of ^{28}SiO was generated from the Dunham coefficients given by Lovas et al. [5] and the dipole moment matrix elements derived by Tipping & Chackerian [9].

We calculate the contribution of the optically thin dust shell based on a simple, spherical model consisting of a mixture of silicate and corundum dust.

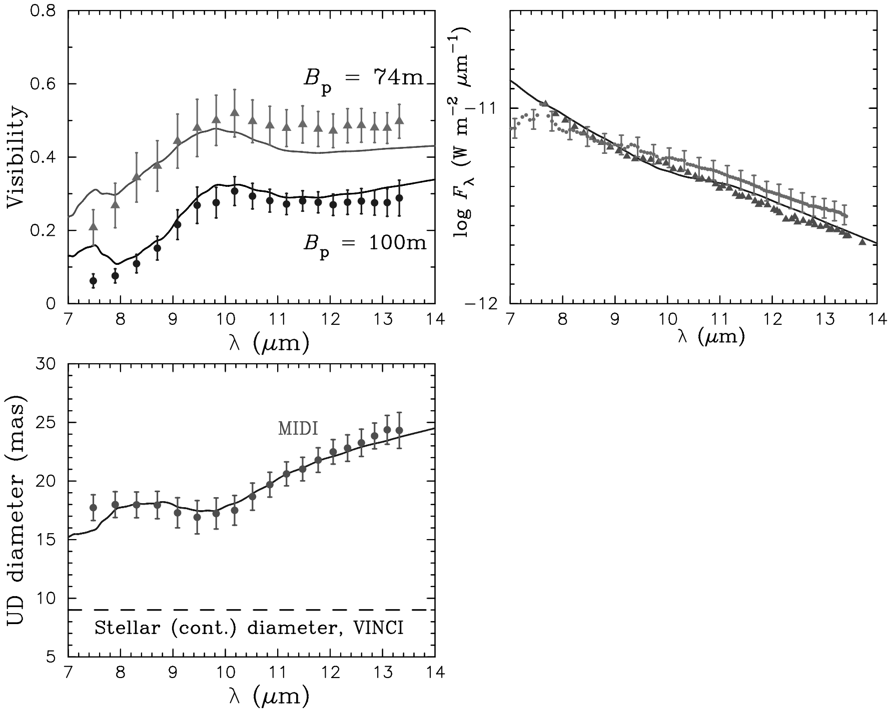

Fig. 2. Upper left: The filled circles and triangles represent the visibilities observed with projected baseline lengths of 99.9 m and 73.7 m, respectively, while the corresponding predicted visibilities are represented with the solid lines. **Lower left**: The filled circles represent the observed uniform-disk diameters, while the solid line represents those predicted for a projected baseline length of 100 m. The dashed line represents the continuum angular diameter estimated from the VINCI observations. **Upper right**: The filled circles represent the calibrated MIDI spectrum of RR Sco obtained from the observations on 2003 Jun 14, while the filled triangles represent the IRAS LRS. The solid line represents the spectrum predicted by the best-fit model.

We calculate the opacity of silicate and corundum in the Mie theory, assuming a single grain size, $a = 0.1$ μm, and using the code published by Bohren & Huffman [1]. We add this dust shell to the warm H_2O +SiO envelope model discussed above, and the total flux and the intensity profile are the sum of the contributions of these two components. The details of the model used in the present work are described in Ohnaka et al. [7].

Figure 2 shows a comparison of the observed visibility, uniform-disk diameter, and spectrum with those predicted by the best-fit model. The parameters of the warm H_2O+SiO envelope are $T_{\rm mol} = 1400 \pm 100$ K, $R_{\rm mol} = 2.3 \pm 0.2\, R_\star$, $N_{\rm H_2O} = 3 \times 10^{21}$ cm^{-2}, and $N_{\rm SiO} = 1 \times 10^{20}$ cm^{-2}, respectively. The uncertainties of the H_2O and SiO column densities are roughly a factor of 2 and 10, respectively. The optical depth of the dust shell is derived to be 0.025 ± 0.01 at 10 μm, which translates into 0.23 in the visual. The inner boundary of the dust shell is found to be 7.5 $R_\star$ with a dust temperature of 700 ± 200 K. We find that the observed spectrum and visibilities can be best reproduced with a dust mixture of 20% silicate and 80% corundum. Figure 2 shows that the observed visibility and uniform-disk diameter are well reproduced from 8 to 13 μm. The predicted spectrum is also in good agreement with the observed MIDI spectrum. The temperatures and column densities of H_2O and SiO gas derived here are in agreement with those previously derived for other oxygen-rich Mira variables by Yamamura et al. [12] and Matsuura et al. [6]. It is also worth noting that the radius of the molecular layer derived here, 2.3 $R_\star$, is consistent with the result obtained by Cotton et al. [2], who found that the SiO maser toward Mira variables originates in the region of 1.7–2.8 $R_\star$.

4 Concluding remarks

The present analysis demonstrates that spectro-interferometry in the mid-infrared is a powerful tool to study the warm molecular envelope, whose properties have mostly been derived from spectroscopic observations up to now. We have shown that the measurement of the wavelength dependence of the angular size over molecular as well as dust spectral features in the mid-infrared provides direct information on the geometrical extension of the warm molecular envelope, and such information, combined with spectral data, can help put more constraints on physical properties of the warm molecular envelope.

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