Mid-infrared interferometry of the Mira variable RR Sco with the VLTI/MIDI instrument

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Abstract

We present the results of the first mid-infrared interferometric observations of the Mira variable RR Sco with the MID-infrared Interferometer (MIDI) coupled to the European Southern Observatory's (ESO) Very Large Telescope Interferometer (VLTI), together with K-band observations using VLTI/VINCI. The observations were carried out in June 2003, when the variability phase of the object was 0.6, using two unit telescopes (UT1 and UT3), as part of the Science Demonstration Time (SDT) program of the instrument. Projected baseline lengths ranged from 73 to 102 m, and a spectral resolution of 30 was employed in the observations, which enabled us to obtain the wavelength dependence of the visibility in the region between 8 to 13 μm. The uniform-disk diameter was found to be 18 mas between 8 and 10 μm, while it gradually increases longward of 10 μm to reach 24 mas at 13 μm. The visibilities obtained over a position angle range of 40° show no major deviation from circular symmetry. The uniform-disk diameter between 8 and 13 μm is 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 with projected baseline lengths of ~15–16 m. Our model calculations show that optically thick emission from a warm molecular envelope consisting of H_2O and SiO can cause the apparent diameter to be much larger than the continuum diameter. We find that the warm molecular envelope model extending to ~2.2 $R_\star$ with a temperature of ~1600 K and column densities of H_2O and SiO of 3×10^{21} cm^{-2} and 1×10^{21} cm^{-2}, respectively, can reproduce the observed uniform-disk diameters between 8 and 10 μm. The observed increase of the uniform-disk diameter longward of 10 μm can be explained by an optically thin dust shell consisting of silicate and corundum grains. The inner radius of the optically thin dust shell is derived to be 7–8 $R_\star$ with a temperature of ~1000 K, and the optical depth at 10 μm is found to be ~0.01.

Introduction

Mid-infrared interferometry provides a unique opportunity to probe the circumstellar environment of Mira variables. Since 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 advent of MIDI (Leinert et al. 2003) at VLTI is expected to allow new possibilities, particularly with the capability to obtain spectrally dispersed interferograms over the wavelength range between 8 and 13 μm.

Here, we present the first spectrally dispersed N-band interferometric observations of the Mira variable RR Sco with VLTI/MIDI and, in addition, K broad-band observations with VLTI/VINCI. RR Sco is a Mira variable with a spectral type of M6II-IIIe-M9 and a period of 281.4 days (Kholopov et al. 1988) Its distance is estimated to be 320 ± 120 pc based on the revised HIPPARCOS parallax of 3.10 ± 1.16 mas (Knapp et al. 2003).

Observations

RR Sco was observed with MIDI at variability phase 0.6 on three consecutive nights in mid-June 2003 within the framework of the Science Demonstration Time (SDT) program. A prism was used to obtain spectrally dispersed interferograms with a spectral resolution of $\lambda/\Delta\lambda \simeq 30$. 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. The data were reduced with the MIDI data reduction software described in detail in Leinert et al. (2004).

In addition to the MIDI measurements, we employed a total of five K-band VLTI/VINCI observations of RR Sco which are publicly available through the ESO archive and which 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. Mean coherence factors were obtained for each series of interferograms with the VINCI data reduction software version 3.0 (Kervella et al. 2004), and we used the results based on the wavelet transform to derive the power spectral density instead of the classical Fourier analysis.

Visibility and spectrum: observations

Figure 1 shows the calibrated visibilities of RR Sco for the seven data sets over the wavelength range from 8 to 13 μm. The visibilities of all seven data sets of RR Sco show a distinct wavelength dependency: a gradual increase from 8 to 10 μm and a roughly constant part longward of 10 μm. The difference in the visibility values at the same wavelength is mainly due to the different projected baseline lengths of the observations.

Thanks to the projection effect, the projected baseline lengths of the seven data sets range from ~70 to ~100 m. Therefore, we plotted the calibrated visibility from each data set against the projected baseline lengths and derived uniform-disk fits for each wavelength. Figure 2 shows uniform disk fits at three representative wavelengths as well as the wavelength dependency of the uniform disk diameter. The wavelength dependence of the visibility translates into an approximately constant uniform-disk diameter of $\sim 18 \pm 1$ mas between 8 and 10 μm, with a very slight dip near 9.5 μm, and a steady increase of the diameter from 18 mas at 10 μm to ~24 mas at 13 μm. Figure 3 shows the calibrated MIDI spectrum of RR Sco, together with the IRAS Low Resolution Spectrum (LRS). Given the accuracy of the MIDI calibrated spectrum, it is not clear whether the difference between the MIDI spectrum and the IRAS LRS can be attributed to a temporal variation of the spectrum. It should also be noted that IRAS LRS exhibits a slight bump at around 9.6 μm, which suggests dust emission. However, in the MIDI spectrum, the region around 9.6 μm is least reliable due to the strong ozone absorption originating in Earth's atmosphere, making it impossible to confirm the presence of this feature.

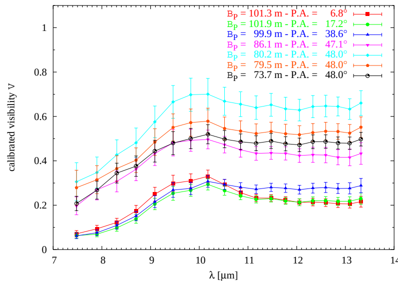


Figure 1: Visibility as a function of wavelength for different projected baseline lengths. For all seven data sets of RR Sco the plot shows the visibility averaged over all calibrators of the corresponding night. The errors are 1σ errors calculated from the variance of the visibility values derived using the different calibrators. The difference in the visibility values at the same wavelength is mainly due to the different projected baseline lengths of the observations.

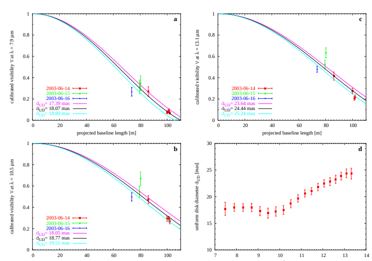
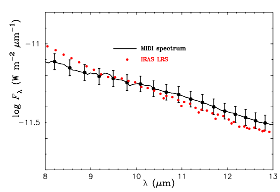


Figure 2: a: Uniform disk fit of the visibilities observed at 7.9 μm. **b:** The same as **a**, but at 10.5 μm. **c:** The same as **a**, but at 13.1 μm. **d:** Uniform-disk diameter as a function of wavelength, derived from uniform disk fits such as shown in **a**, **b**, and **c**.

Figure 3: N-band spectra of RR Sco. The black solid line represents the calibrated MIDI spectrum, while the IRAS LRS is plotted with the red circles.



Visibility and spectrum: modeling

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 $R_\star$, and the star is surrounded by a warm molecular envelope consisting of H_2O and SiO gas with a constant temperature and density, extending to $R_{\rm mol}$. 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 ($R_{\rm mol}$ and $T_{\rm mol}$, respectively) as well as the column densities of H_2O and SiO ($N_{\rm H_2O}$ and $N_{\rm SiO}$, respectively) in the radial direction. We estimate the angular continuum radius to be 4.5 mas based on the K-band uniform-disk diameter measured with VINCI.

We first calculate the line opacity due to H_2O and SiO in the wavelength range between 8 and 13 μm based on the HITEMP H_2O line list and the SiO line list generated from the Dunham coefficients given by Lovas et al. (1981) and the dipole moment matrix elements derived by Tipping & Chackerian (1981). 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.

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. The averaged opacity of the mixture of silicate and corundum is calculated with different ratios of the two components. Assuming a dust density distribution proportional to r^{-2}, the temperature distribution in the dust shell is calculated from thermal balance in the optically thin limit. The input parameters are the temperature at the inner boundary and the optical depth of the dust shell. The outer radius of the dust shell is set to be 100 $R_\star$, but it does not have a major effect on the resulting flux and intensity profile in the relevant spectral range.

Once the molecular and dust opacities have been calculated, the monochromatic intensity profile, monochromatic visibility squared, and emergent flux are calculated with a wavenumber interval of 0.01 cm^{-1}. The calculated monochromatic visibility squared is then spectrally convolved to match the spectral resolution of 30, which was used in the SDT observations, and the uniform-disk diameter is derived from this spectrally convolved visibility for a given projected baseline length (see Ohnaka et al. 2004 for details).

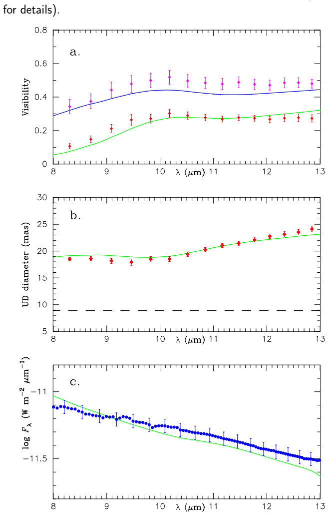


Figure 4: Comparison between the observed visibility (**a**), uniform-disk diameter (**b**), and spectrum (**c**) and those predicted by the best-fit model for RR Sco. The parameters of the H_2O+SiO envelope are $T_{\rm mol}$ = 1600 K, $R_{\rm mol}$ = 2.2 $R_\star$, $N_{\rm H_2O}$ = 3×10^{21} cm^{-2}, and $N_{\rm SiO}$ = 1×10^{21} cm^{-2}. The dust shell has an inner radius of 7.5 $R_\star$ with a temperature of 1000 K and an optical depth of 0.01 at 10 μm. **a**: The red and purple circles 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 green and blue solid lines, respectively. **b**: The red filled circles represent the observed values, which are the same as in Fig. 2d, while the green solid line represents the predicted uniform-disk diameter for a projected baseline length of 100 m. The dashed line represents the angular continuum diameter assumed in the calculation. **c**: The blue filled circles represent the calibrated spectrum of RR Sco obtained from the observations on 2003 Jun 14 (the same as the black solid line in Fig. 3). The green solid line represents the spectrum predicted from the best-fit model.

Figure 4 shows a comparison of the observed visibility, uniform-disk diameter, and spectrum with those predicted from the best-fit model. We find that the observed spectrum and visibilities can be best reproduced with a dust mixture of 20% silicate and 80% corundum. The optical depth of the dust shell is derived to be 0.01 ± 0.005 at 10 μm, which translates into 0.03 in the visual. The inner boundary of the dust shell is found to be 7.5 $R_\star$ with a dust temperature of 1000 ± 200 K. The parameters of the warm H_2O+SiO envelope are $T_{\rm mol} = 1600 \pm 100$ K, $R_{\rm mol} = 2.2 \pm 0.2$ $R_\star$, $N_{\rm H_2O}$ = 3×10^{21} cm^{-2}, and $N_{\rm SiO} = 1 \times 10^{21}$ cm^{-2}, respectively. Figure 4 illustrates that the observed visibility and uniform-disk diameter are well reproduced from 8 μm to 12 μm. The predicted spectrum is also in good agreement with the observed MIDI spectrum. The agreement becomes a little poorer longward of 12 μm, but this may be due to the presence of the so-called 13 μm feature, whose carrier is, however, not yet identified (Sloan et al. 2003).

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