

## **Polychromatic interferometry of Mira variables**

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**Abstract.** We report on our project to study the atmospheric structure and the circumstellar environment of evolved stars using optical and radio long-baseline interferometry. VLTI observations of the cool giants  $\psi$  Phe,  $\gamma$  Sge, and  $\alpha$  Cet were previously used to calibrate stellar model atmospheres of regular non-pulsating cool giants as well as to derive high-precision fundamental parameters. Previous VLTI observations of the Mira variable R Leo are consistent with self-excited dynamic Mira model atmospheres that include molecular shells close to continuum-forming layers. Coordinated observations at near-infrared mid-infrared, and radio wavelengths of evolved stars were conducted, aiming at a better understanding of the stellar pulsation, the mass-loss process, and the triggering and formation of asymmetric structures. Results from our pilot study on the Mira variable S Ori show that the SiO maser reside at a distance of about 2 photospheric radii, a result that is virtually free of the usual uncertainty inherent in comparing observations of variable stars often widely separated in time. New coordinated VLTI/MIDI and VLBA observations of S Ori at concurrent epochs were conducted, and first preliminary results are shown.

### **1. Introduction**

The evolution of cool luminous stars, including Mira variables, is accompanied by significant mass-loss to the circumstellar environment (CSE). This mass-loss process significantly affects the further stellar evolution, and is one of the most important sources for the enrichment of the interstellar medium. The detailed nature of the mass-loss process from evolved stars, and especially its connection with the pulsation mechanism in the case of Mira variable stars, is a matter of current investigation.

The conditions near a stellar surface can well be studied by means of optical long-baseline interferometry, which has provided information regarding the stellar photospheric diameter, effective temperature, centre-to-limb intensity variations (CLVs), and the molecular layers for a number of Mira variables. The

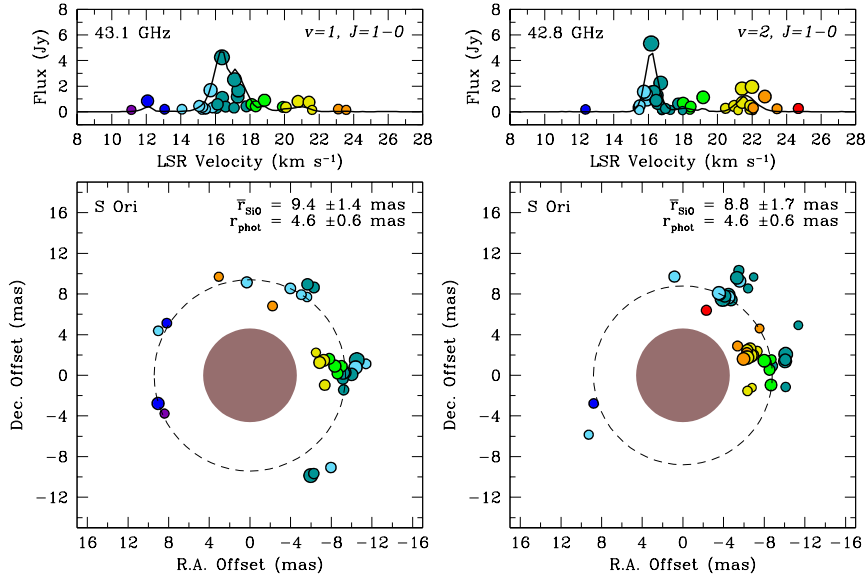


Figure 1. Result from the first-ever coordinated observations between the VLTI and the VLBA. Shown are the images of the (left)  $v = 1$ ,  $J = 1 - 0$ , 43.1 GHz and (right)  $v = 2$ ,  $J = 1 - 0$ , 42.8 GHz SiO maser emission toward S Ori obtained with the VLBA, together with the photospheric radius obtained quasi-simultaneously with the instrument VINCI of the VLTI. From Boboltz & Wittkowski (2005).

structure of the molecular shells located between the photosphere and the dust formation zone, as well as the dust shell itself can be probed by mid-infrared interferometry. Complementary information regarding the molecular shells around oxygen-rich AGB stars can be obtained by observing the maser radiation that some of these molecules emit. Maser emission from the three most common masing molecules, SiO, H<sub>2</sub>O and OH, traces regions of the CSE on angular scales from tens of milliarcseconds to a few arcseconds.

## 2. Studies of non-pulsating giants

A good knowledge of the detailed atmospheric structure of non-pulsating giants and of methods of confronting atmosphere models with observations is an ideal starting point for the study of pulsating giants. Confrontation of model atmospheres with observations is often performed by spatial integration of the model radiation field over the whole stellar disc, spectral integration to broadband colours and/or spectrograms of different spectral resolution, and subsequent comparison to observed broadband photometry, spectro-photometry, or spectroscopy. Optical interferometry provides a further and more direct test of stellar atmosphere models by resolving the stellar disc and measuring the centre-to-limb intensity variation (CLV) across the stellar disc.

For instance, Wittkowski et al. (2006a) presented coordinated near-infrared  $K$ -band interferometric and optical spectroscopic observations of the M 1.5 giant Menkar obtained with the instruments VINCI and UVES. It was shown that

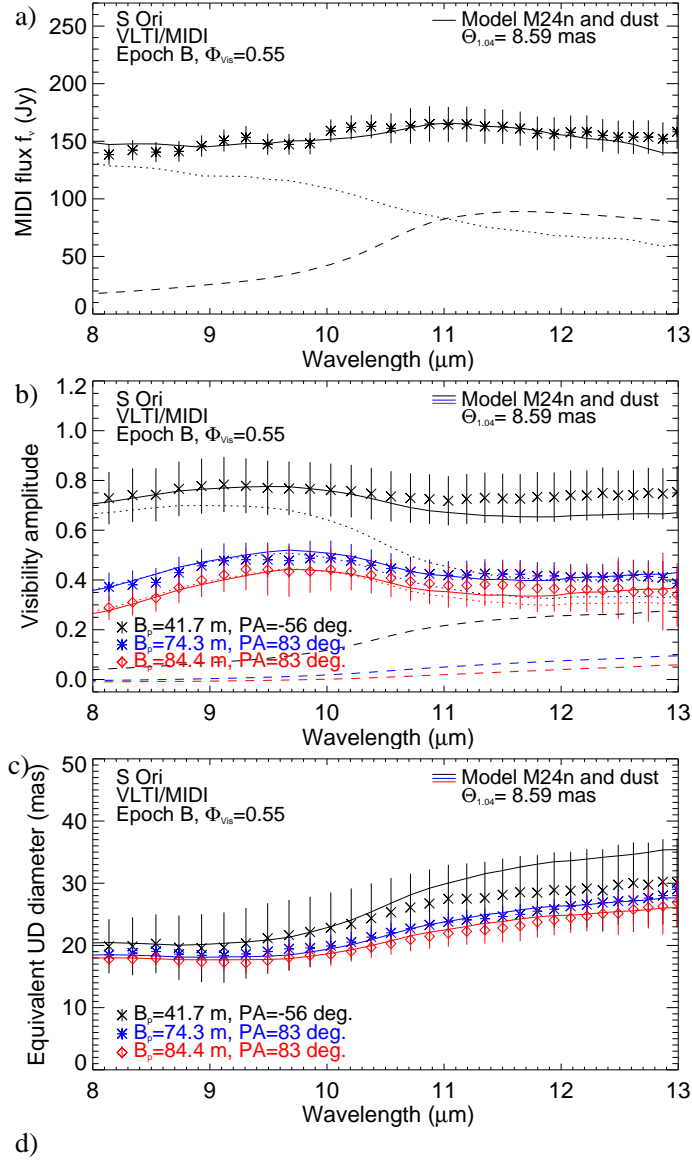


Figure 2. Preliminary results from our new VLT/MIDI 8-13  $\mu\text{m}$  interferometry of S Ori at one of four epochs, stellar phases 0.55. Shown are (a) the MIDI flux, (b) the visibility values, and (3) the equivalent uniform disc diameter values, together with a preliminary model. The preliminary model consists of the dust-free atmosphere model M24n (Ireland et al. (2004b)) and an added dust shell of  $\text{Al}_2\text{O}_3$  with inner radius  $R_{\text{in}} = 2R_*$ , density  $\propto r^{-2.6}$ ,  $\tau_0(\text{Al}_2\text{O}_3) = 1.6$ . From Wittkowski et al., in preparation.

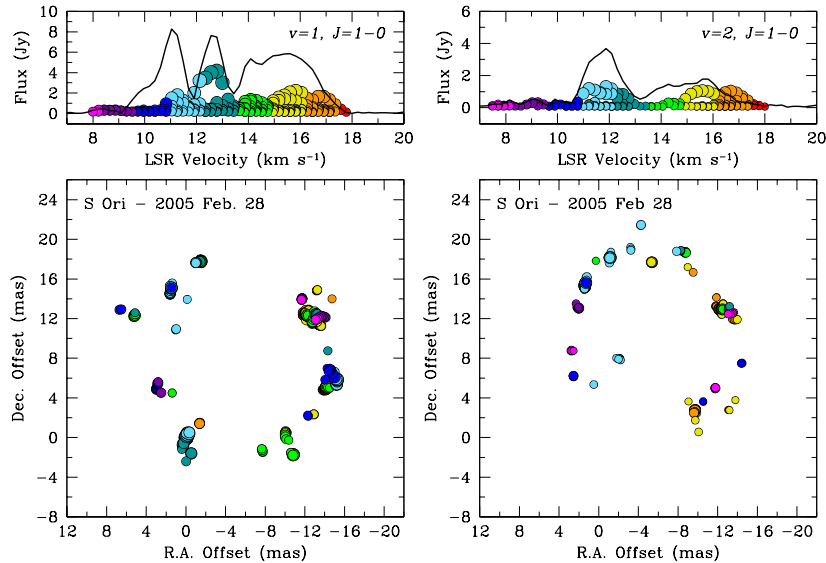


Figure 3. Preliminary results from our new VLBA interferometry of S Ori. Shown are the images of the (left)  $v = 1$ ,  $J = 1 - 0$ , 43.1 GHz and (right)  $v = 2$ ,  $J = 1 - 0$ , 42.8 GHz SiO maser emission toward S Ori, obtained at the same epoch as the VLTI/MIDI observations in Fig. 2. The colours denote the LOS velocity structure. From Wittkowski et al., in preparation.

the derived PHOENIX model atmosphere for Menkar is consistent with both, the measured strength of the limb-darkening in the near-infrared  $K$ -band and the profiles of spectral bands around selected atomic lines and TiO bandheads from 370 nm to 1000 nm. Other recent interferometric studies of non-pulsating giants using optical interferometry include those of the M0 giant  $\gamma$  Sge by Wittkowski et al. (2006b), and of the M4 giant  $\psi$  Phe by Wittkowski et al. (2004). These studies also result in precise angular diameters, and together with the bolometric flux and distance in precise effective temperatures and absolute radii.

### 3. Studies of Mira variables

With respect to interferometric studies of non-pulsating giants as described in the previous section, studies of Mira variables need to consider in addition the stellar pulsation, the effects from molecular layers close to continuum-forming layers, as well as the formation of dust shells.

For instance, Fedele et al. (2005) recently showed that observed near-infrared  $K$ -band visibilities of the prototype Mira variable R Leo are very different from uniform disc models already in the first lobe of the visibility function, and correspond well to predictions by self-excited dynamic Mira model atmospheres that include effects from close molecular layers by Ireland et al. (2004a; 2004b), and references therein.

Ohnaka et al. (2005) used the spectro-interferometric capabilities of the mid-infrared VLTI/MIDI facility for observations of the Mira star RR Sco. The model used in this work includes a warm molecular layer consisting of SiO and

H<sub>2</sub>O extending to  $\sim 2.3 R_{\star}$  as well as an optically thin dust shell of corundum and silicate with an inner radius of  $\sim 7\text{--}8 R_{\star}$ . This model can well reproduce the measured mid-infrared visibility and flux values, as well as the near-infrared apparent diameter.

#### 4. Joint VLTI/VLBA observations of Mira variables

Observational results regarding the detailed relationships between the stellar photosphere, the molecular layer, the dust shell, and the SiO maser ring of Mira stars often suffer from uncertainties inherent in comparing observations of variable stars widely separated in time and stellar phase, as discussed in Boboltz & Wittkowski (2005). To overcome this limitation, we have established a programme of concurrent infrared interferometry using the VLTI and radio interferometry using the VLBA. The former aims at constraining the photospheric radius, the characteristics of close molecular layers, and parameters of the dust shell. The latter aims at contemporaneously mapping the SiO maser emission. Figure 1 shows the results from our pilot study on the Mira variable S Ori that included coordinated near-infrared *K*-band interferometry to constrain the stellar photospheric diameter and VLBA mapping of the SiO maser radiation toward this source. We derived average distances of the SiO maser spots from the centre of their distribution at phase 0.73 of 9.4 mas and 8.8 mas for the 43.1 GHz and 42.8 GHz transitions, respectively. Quasi-simultaneously, the photospheric diameter was measured to 9.2 mas which puts the masers at distances from the stellar centre of  $2.0 R_{\star}$  and  $1.9 R_{\star}$  for the two transitions. This result is virtually free of the usual uncertainty inherent in comparing observations of variable stars often widely separated in time.

We have conducted new coordinated observations of S Ori using mid-infrared interferometry (VLTI/MIDI) and SiO maser observations (VLBA) at three concurrent epochs/stellar phases. The mid-infrared data are modelled using the dust-free dynamic model atmospheres by Ireland et al. (2004a; 2004b), and references therein, and we have added an ad-hoc radiative transfer model of the dust shell. This study is currently in progress. Figs. 2 and 3 show preliminary results in order to illustrate the approach. The final results will be reported elsewhere by the authors of these proceedings.

Further planned studies include near-infrared interferometry using AMBER, observations of OH and H<sub>2</sub>O maser emission, and a larger sample of targets including supergiants.

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