

## The Extended Atmospheres of Mira Variables Probed by VLTI, VLBA, and APEX

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**Abstract.** We present an overview of our project to study the extended atmospheres and dust formation zones of Mira stars using coordinated observations with the Very Large Telescope Interferometer (VLTI), the Very Long Baseline Array (VLBA), and the Atacama Pathfinder Experiment (APEX). The data are interpreted using an approach of combining recent dynamic model atmospheres with a radiative transfer model of the dust shell, and combining the resulting model structure with a maser propagation model.

### 1. Introduction and Project Outline

Mass loss becomes increasingly important as an evolving star approaches the tip of the asymptotic giant branch (AGB). While the mass-loss process during the AGB phase is the most important driver for further stellar evolution toward the planetary nebula phase, details of the mass-loss process and its connection to the structure of the extended atmosphere and stellar pulsation are not well understood and are currently a matter of debate.

Here, we present an overview of our established project of coordinated interferometric observations at infrared and radio wavelengths. Our goal is to establish the radial structure and kinematics of the stellar atmosphere and the circumstellar environment to understand better the mass-loss process and its connection to stellar pulsation. We also aim at tracing asymmetric structures from small to large distances in order to constrain

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shaping processes during the AGB evolution, which may lead to the observed diversity of shapes of planetary nebulae. We use two of the highest resolution interferometers in the world, the Very Large Telescope Interferometer (VLTI) and the Very Long Baseline Array (VLBA), to study AGB stars and their circumstellar envelopes from near-infrared to radio wavelengths. For some sources, we have included near-infrared broad-band photometry obtained at the South African Astronomical Observatory (SAAO) in order to derive values of the effective temperature. We have also started to use the Atacama Pathfinder Experiment (APEX) to investigate the line strengths and variability of high frequency SiO maser emission.

## 2. Observations

Our pilot study included coordinated observations of the Mira variable S Ori including VINCI *K*-band measurements at the VLTI and SiO maser measurements at the VLBA (Boboltz & Wittkowski 2005). For the Mira variables S Ori, GX Mon and RR Aql and the supergiant AH Sco, we obtained long-term mid-infrared interferometry covering several pulsation cycles using the MIDI instrument at the VLTI coordinated with VLBA SiO (42.9 GHz and 43.1 GHz) observations (Wittkowski et al. 2007, Karovicova et al., these proceedings). For the Mira variables R Cnc and X Hya, we have coordinated near-infrared interferometry (VLTI/AMBER), mid-infrared interferometry (VLTI/MIDI), VLBA/SiO maser and VLBA/H<sub>2</sub>O maser observations, and near-infrared photometry at the SAAO (work in progress). Most recently, measurements of the  $\nu = 1$  and  $\nu = 2$ ,  $J = 7-6$  SiO maser transitions toward our program stars were obtained at two epochs using APEX.

## 3. Modeling

The P and M model series by Ireland et al. (2004a,b) were chosen as the currently best available option to describe dust-free Mira star atmospheres. Wittkowski et al. (2007) have added an ad-hoc radiative transfer model to these model series to describe the dust shell as observed with the mid-infrared interferometric instrument MIDI using the radiative transfer code `mcsim_mpi` by Ohnaka et al. (2007). Gray et al. (2009) have combined these hydrodynamic atmosphere plus dust-shell models with a maser propagation code in order to describe the SiO maser observations. Most recently, we have also used new dynamic atmosphere series (the CODEX series) by Ireland, Scholz, & Wood (2008), which uses the opacity-sampling method and is available for additional stellar parameters compared to the P/M series.

## 4. Results

The pilot study on the Mira variable S Ori (Boboltz & Wittkowski 2005) revealed that the SiO maser ring radii lie at  $2.0 R_{\text{cont}}$  (43.1 GHz transition) and  $1.9 R_{\text{cont}}$  (42.8 GHz transition) at phase 0.7. The stellar diameter was estimated by measuring the uniform disk diameter and correcting it for the continuum diameter using dynamic model atmospheres as described in Section 3. This result is free of the usual uncertainty inherent in comparing observations widely spaced in phase and/or using directly uniform disk diameters which may be contaminated by extended molecular layers. Fedele et al.

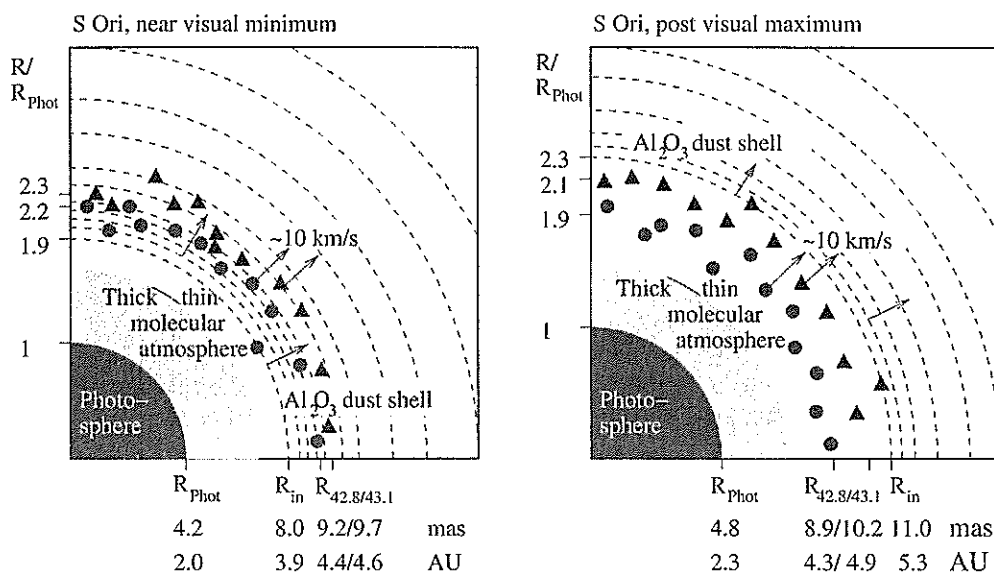


Figure 1. Sketch of the radial structure of S Ori's circumstellar envelope at (left) near-minimum and (right) post-maximum visual phase from Wittkowski et al. (2007). Shown are the locations of the continuum photosphere (dark gray), the at *N*-band optically thick molecular atmosphere (medium dark gray), the at *N*-band optically thin molecular atmosphere (light gray), the  $\text{Al}_2\text{O}_3$  dust shell (dashed arcs), and the 42.8 / 43.1 GHz SiO maser spots (circles/triangles).

(2005) estimated, in an analogous way, SiO maser ring radii of  $1.9 R_{\text{cont}}$  and  $1.8 R_{\text{cont}}$ , respectively, for the Mira variable R Leo at phase 0.1.

Mid-infrared interferometric data of S Ori were taken concurrently with three additional epochs of VLBA observations of the same SiO maser transitions (Wittkowski et al. 2007). The modeling of the MIDI data results in phase-dependent continuum photospheric angular diameters. The dust shell can best be modeled with  $\text{Al}_2\text{O}_3$  grains alone located close to the stellar photosphere with inner radii between 1.8 and 2.4 photospheric radii. Mean SiO maser ring radii are found to lie between about 1.9 and 2.4 stellar continuum radii. The maser spots mark the region of the molecular atmospheric layers shortly outside the steepest decrease of the mid-infrared model intensity profile. These results suggest that the SiO maser shells are co-located with the  $\text{Al}_2\text{O}_3$  dust shell near minimum visual phase. Their kinematics show that a velocity gradient appears at all epochs, with masers toward the blue- and red-shifted ends of the spectrum lying closer to the center of the distribution than masers at intermediate velocities. This phenomenon is interpreted as a radial gas expansion with a velocity of about  $10 \text{ km s}^{-1}$ . Figure 1 is a sketch of the radial structure of S Ori's circumstellar environment as derived from this study. A similar – but longer – study of the Mira variable RR Aql, which shows a silicate dust chemistry, is presented by Karovicova et al. in these proceedings.

The combination of a dynamic model atmospheres plus dust shell model with the maser propagation model by Gray et al. (2009) shows that the modeled SiO masers form in rings with radii consistent with those found in the VLBA observations described above and in earlier models. This agreement requires the adoption of a radio photosphere of radius about twice that of the near-infrared continuum photosphere, in

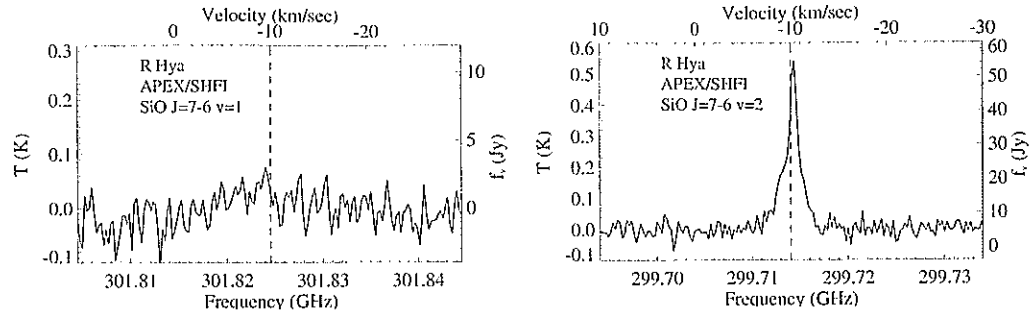


Figure 2. APEX/SHFI observations of the  $J = 7 - 6$ ,  $\nu = 1$  (left) and  $\nu = 2$  (right) SiO maser transitions of R Hya at one epoch. R Hya shows only the  $\nu = 2$  transition at this phase. Other sources have shown both transitions (e.g. R Leo), or  $\nu = 1$  but not  $\nu = 2$  (e.g.  $\alpha$  Cet).

agreement with observations. Maser rings, a shock, and the  $8.1 \mu\text{m}$  radius, dominated by optically thick water layers, appear to be closely related. The maser ring variability and number of spots may not be consistent with observations, which may be explained by re-setting masers in the model at each phase.

Near-infrared spectro-interferometric observations of AGB stars using the AMBER instrument were first obtained by Wittkowski et al. (2008). These observations covering 29 spectral channels between  $1.29 \mu\text{m}$  and  $2.32 \mu\text{m}$  exhibit significant variations as a function of spectral channel that can only be explained by a variation of the apparent angular size with wavelength. This ‘bumpy’ visibility curve is interpreted as a signature of molecular layers lying above the continuum-forming photosphere, at near-infrared wavelengths mostly CO and H<sub>2</sub>O. The variation of visibility and corresponding diameter values resemble well the predictions by dynamic model atmospheres that naturally include these atmospheric molecular layers. Similar bumpy visibility curves were subsequently also seen for the red supergiant VX Sgr (Chiavassa et al. 2010), the semi-regular AGB star RS Cap (Marti-Vidal et al., in preparation), and three OH/IR stars (Ruiz Velasco et al., these proceedings), indicating that molecular layers close to the star may be a common phenomenon of cool evolved stars.

Medium resolution ( $R \sim 1500$ ) visibility functions of the Mira variable R Cnc obtained within the project discussed here confirm the conclusion that Mira variables show wavelength-dependent angular diameters when observed with spectro-interferometric techniques. In particular, the CO band-heads are nicely visible with the AMBER medium resolution mode. The data are well consistent with predictions by dynamic model atmospheres of the P/M as well as the CODEX series, where the latter provides better agreement, in particular for the CO band-heads. R Cnc shows closure phase values that are significantly different from  $0^\circ$  and  $180^\circ$ , thus indicating a significant deviation from point symmetry. The interpretation of the closure phase measurements is in progress. They might indicate a complex non-spherical stratification of the extended atmosphere, and may reveal whether observed asymmetries are located near the photosphere or in the outer molecular layers. The measured angular diameter values together with the SAAO photometry results in phase-dependent effective temperature values that are roughly consistent with the effective temperatures of the best-fitting model atmospheres of the series.

Our recent APEX observations of the  $\nu = 1$  and  $\nu = 2$ ,  $J = 7-6$  SiO maser transitions of AGB stars show a variability of the maser intensity that is stronger than for the centimeter SiO maser transitions. Also, different ratios between the  $\nu = 1$  and  $\nu = 2$  transitions have been detected for different sources and phases, and sometimes only one of the two transitions is present (Figure 2). The combination of dynamic atmosphere and maser propagation models by Gray et al. (2009) show the  $\nu = 1$  transition but not the  $\nu = 2$  transition. Earlier such models (Humphreys et al. 2002) showed both transitions; these had stronger shocks and higher post-shock temperatures compared to the more recent models. It is also known that infrared line overlap of SiO and H<sub>2</sub>O can deeply effect the pumping of some SiO maser transitions and lead to anomalous maser intensities (e.g. Bujarrabal et al. 1996).

## 5. Summary

We have observed a sample of AGB stars with near-infrared, mid-infrared, and radio interferometry. Near-infrared spectro-interferometry has been shown to be a powerful tool to study the complex atmosphere of AGB stars including atmospheric molecular layers, most importantly those of H<sub>2</sub>O and CO. These observations are nicely consistent with predictions by recent dynamic model atmospheres. Near-infrared closure phase measurements indicate a complex non-spherical stratification of the atmosphere. The addition of near-infrared photometry allows us to determine phase-dependent effective temperature values. Mid-infrared interferometry constrains dust shell parameters including Al<sub>2</sub>O<sub>3</sub> dust with inner boundary radii of about 2 photospheric radii and silicate dust with inner boundary radii of about 4 photospheric radii. SiO maser transitions observed with the VLBA (42.8 GHz and 43.1 GHz) lie in the extended atmosphere seen by near-infrared and mid-infrared interferometry, and they may be co-located with Al<sub>2</sub>O<sub>3</sub> dust. Their kinematics indicate motion such as outflow. The observed location relative to the stellar photosphere is consistent with predictions of combined hydrodynamic models and maser propagation models. APEX millimeter observations indicate high-frequency SiO masers that are probably located very close to the photosphere, and that show strong variability. We plan to add millimeter interferometry to this study using the Atacama Large Millimeter Array (ALMA) in order to obtain maps of high-frequency SiO masers.

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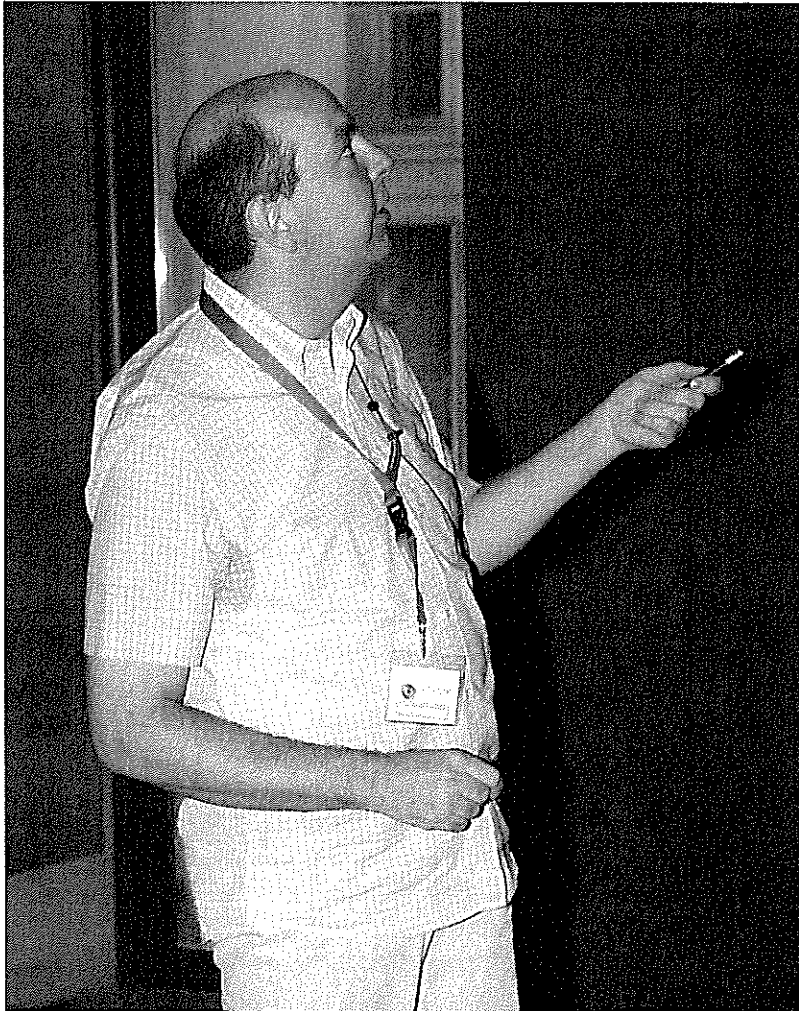
## Discussion

*Posch:* Is it true that the aluminum dust in your S Ori model has a patchy structure?

*Wittkowski:* The model is a spherically symmetric model, and we can not derive information on a patchy structure of the dust yet.

*Sloan:* Are the position and composition of the dust assumed or determined from the observations?

*Wittkowski:* We compare mid-infrared interferometric observations to a model of a dynamic atmosphere and an ad-hoc radiative transfer model of a dust shell. So far, we assume the dust to consist of  $\text{Al}_2\text{O}_3$  and silicates with independent inner radii and density distribution. The inner radius and optical depth of each considered dust species comes from a fit of observations to the model.



Markus Wittkowski.