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VLTI observations of AGB stars

M. Wittkowski[1], D. A. Boboltz[2], T. Driebe[3], and K. Ohnaka[3]

[1] European Southern Observatory, Garching, Germany
[2] U.S. Naval Observatory, Washington, DC, USA
[3] Max-Planck-Institut für Radioastronomie, Bonn, Germany

Abstract. We report on recent observations of AGB stars obtained with the VLT Interferometer (VLTI). We illustrate in general the potential of interferometric measurements to study stellar atmospheres and circumstellar envelopes, and demonstrate in particular the advantages of a coordinated multi-wavelength approach including near/mid-infrared as well as radio interferometry. We report on studies of the atmospheric structure of non-Mira and Mira variable giants. We have used VLTI observations of the near- and mid-infrared stellar sizes and concurrent VLBA observations of the SiO maser emission. So far, this project includes studies of the Mira stars S Ori and RR Aql as well as of the supergiant AH Sco. The results from our first epochs of S Ori measurements have recently been published and the main results are reviewed here. The S Ori maser ring is found to lie at a mean distance of approximately 2 stellar radii, a result that is virtually free of the usual uncertainty inherent in comparing observations of variable stars widely separated in time and stellar phase. We discuss the status of our more recent S Ori, RR Aql, and AH Sco observations, and present an outlook on the continuation of our project.

Key words. Stars: AGB and post-AGB – Stars: atmospheres – Stars: late-type – Techniques: interferometric – masers

1. Introduction

The evolution of cool luminous stars, including Mira variables, is accompanied by significant mass-loss to the circumstellar environment (CSE) with mass-loss rates of up to 10^{-7} – $10^{-4}\,M_{\odot}$/year. The detailed structure of the CSE, the detailed physical nature of this mass-loss process from evolved stars, and especially its connection with the pulsation mechanism in the case of Mira variable stars, are not well understood. Furthermore, one of the basic unknowns in the study of late-type stars is the mechanism by which usually spherically symmetric stars on the asymptotic giant branch (AGB) evolve to form axisymmetric or bipolar planetary nebulae (PNe). There is evidence for some asymmetric structures already at the AGB or supergiant stage (e.g., Weigelt et al. 1996, 1998; Wittkowski et al. 1998; Monnier et al. 1999).

Coordinated multi-wavelength studies (near-infrared, mid-infrared, radio, millimeter) of the stellar surface (photosphere) *and* the CSE at different distances from the stellar photosphere and obtained at corresponding cycle/phase values of the stellar variability curve are best suited to improve our general understanding of the atmospheric structure, the CSE, the mass-loss process, and ultimately

Send offprint requests to: M. Wittkowski, Email: mwittkow@eso.org

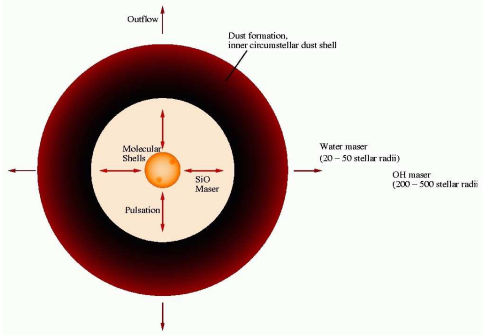

Fig. 1. Sketch of a Mira variable star and its circumstellar envelope (CSE). A multi-wavelength study (MIDI/AMBER/VLBA) is well suited to probe the different regions shown here. Owing to the stellar variability, only contemporaneous observations are meaningful.

of the evolution of symmetric AGB stars toward axisymmetric or bipolar planetary nebulae. Fig. 1 shows a schematic view of a Mira variable star, indicating the different regions that can be probed by different techniques/wavelength ranges (VLTI/AMBER, VLTI/MIDI, VLBA/maser, ALMA).

The conditions near the stellar surface can best be studied by means of optical/near-infrared long-baseline interferometry (see, e.g., Haniff et al. 1995; Wittkowski et al. 2001; Thompson et al. 2002; Wittkowski et al. 2004; Woodruff et al. 2004; Boboltz & Wittkowski 2005; Fedele et al. 2005). The structure and physical parameters of the molecular shells located between the photosphere and the dust formation zone, as well as of the dust shell itself can be probed by mid-infrared interferometry (e.g., Danchi et al. 1994; Ohnaka et al. 2005).

Complementary information regarding the molecular shells can be obtained by observing the maser radiation that some of these molecules emit. The structure and dynamics of the CSE of Mira variables and other evolved stars has been investigated by mapping SiO maser emission at typically about 2 stellar radii toward these stars using very long baseline interferometry (VLBI) at radio wavelengths (e.g., Boboltz et al. 1997; Kemabll & Diamond 1997; Boboltz & Wittkowski 2005).

Results regarding the relationships between the different regions mentioned above and shown in Fig. 1 suffer often from uncertainties inherent in comparing observations of variable stars widely separated in time and stellar phase (see the discussion in Boboltz & Wittkowski 2005). Both, the photospheric stellar size, as well as the mean diameter of the SiO maser shell are known to vary as a function of the stellar variability phase with amplitudes of 20-50% (Ireland et al. 2004; Thompson et al. 2002; Humphreys et al. 2002; Diamond & Kemball 2003).

To overcome these limitations, we have established a program of coordinated and concurrent observations at near-infrared, mid-infrared, and radio wavelengths of evolved stars, aiming at a better understanding of the structure of the CSE, of the mass-loss process, and of the triggering and formation of asymmetric structures.

2. The atmospheric structure of non-Mira and Mira giants

Fundamental parameters, most importantly radii and effective temperatures, of regular cool giant stars have frequently been obtained with interferometric and other high angular resolution techniques, thanks to the favorable brightness and size of these stars. Further parameters of the stellar structure, as the strength of the limb-darkening effect, can be studied when more than one resolution element across the stellar disk is employed. Through the direct measurement of the center-to-limb intensity variation (CLV) across stellar disks and their close environments, interferometry probes the vertical temperature profile, as well as horizontal inhomogeneities. Such direct limb-darkening studies have been accomplished for a relatively small number of stars using different interferometric facilities (including, for instance, Hanbury Brown et al. 1973; Quirrenbach et al. 1996; Hajian et al. 1998; Wittkowski et al. 2001, 2004).

Recent optical multi-wavelength measurements of the cool giants γ Sge and BY Boo

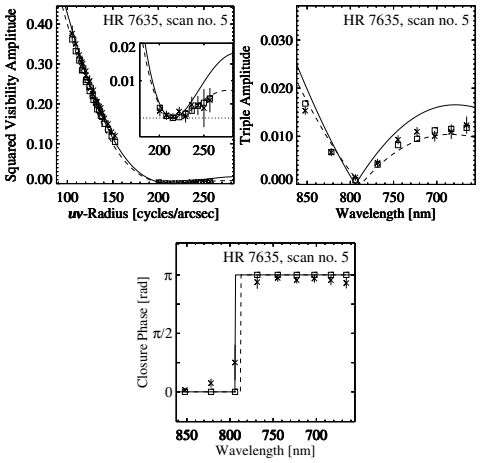

Fig. 2. NPOI limb-darkening observations (squared visibility amplitude, triple amplitude, closure phase) of the M0 giant γ Sge, together with a comparison to the best fitting ATLAS 9 model atmosphere prediction (squares). For comparison, the solid line denotes a uniform disk model, and the dashed line a fully-darkened disk model. ATLAS 9 models with variations of $T_{\rm eff}$ and $\log g$ result in significantly different model predictions. From Wittkowski et al. (2001).

(Wittkowski et al. 2001) succeeded not only in directly detecting the limb-darkening effect, but also in constraining ATLAS 9 (Kurucz 1993) model atmosphere parameters. Fig. 2 shows one dataset including squared visibility amplitudes, triple amplitudes, and closure phases of the M0 giant γ Sge obtained with NPOI, together with a comparison to the best fitting ATLAS 9 model atmosphere prediction. ATLAS 9 models with variations of $T_{\rm eff}$ and $\log g$ result in significantly different model predictions. By this direct comparison of the NPOI data to the ATLAS 9 models alone, the effective temperature of γ Sge is constrained to 4160±100 K. The limb-darkening observations are less sensitive to variations of the surface gravity, and $\log g$ is constrained to 0.9±1.0 (Wittkowski et al. 2001). These results are well consistent with independent estimates, such as calibrations of the spectral type.

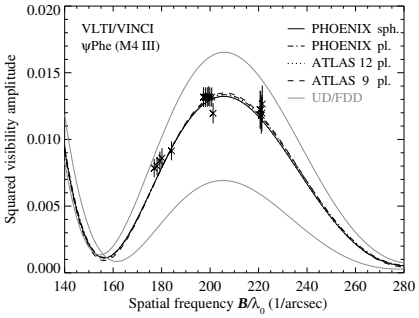

Fig. 3. VLTI limb-darkening observations of the M4 giant ψ Phe (Wittkowski et al. 2004).

The first limb-darkening observation obtained with the VLTI succeeded in the early commissioning phase of the VLTI (Wittkowski et al. 2004). Using the VINCI instrument, K-band visibilities of the M4 giant ψ Phe were measured in the first and second lobe of the visibility function. These observations were found to be consistent with predictions by PHOENIX and ATLAS model atmospheres, the parameters for which were constrained by comparison to available spectrophotometry and theoretical stellar evolutionary tracks (see Fig. 3). Such limb-darkening observations also result in very precise and accurate radius estimates because of the precise description of the CLV. Future use of the spectro-interferometric capabilities of AMBER and MIDI will enable us to study the wavelength-dependence of the limb-darkening effect, which results in stronger tests and constraints of the model atmospheres than these broad-band observations (cf. the wavelength-dependent optical studies with NPOI as described above).

For cool pulsating Mira stars, the CLVs are expected to be more complex than for non-pulsating M giants due to the effects of molecular layers close to the continuum-forming layers. Self-excited hydrodynamic model atmospheres of Mira stars have been presented (Hofmann et al. 1998; Tej et al. 2003; Ireland et al. 2004,Scholz & Wood, private communication). Different radius definitions, such as the Rosseland mean radius, the continuum radius, or the radius at which the filter-averaged intensity drops by 50%, may result in different val-

ues for the same CLV. On these topics, see also Scholz (2003). However, interferometric measurements covering a range of spatial frequencies can directly be compared to CLV predictions by these model atmospheres without the need of a particular radius definition. At pre-maximum stellar phases, when the temperature is highest, the broad-band CLVs are less contaminated by molecular layers, and different radius definitions agree relatively well (Scholz & Wood, private communication).

K-band VINCI observations of the prototype Mira stars *o* Cet and R Leo have been presented by Woodruff et al. (2004) and Fedele et al. (2005), respectively. These measurements at post-maximum stellar phases indicate indeed *K*-band CLVs which are clearly different from a uniform disk profile already in the first lobe of the visibility function. The measured visibility values were found to be consistent with predictions by the self-excited dynamic Mira model atmospheres described above that include molecular shells close to continuum-forming layers.

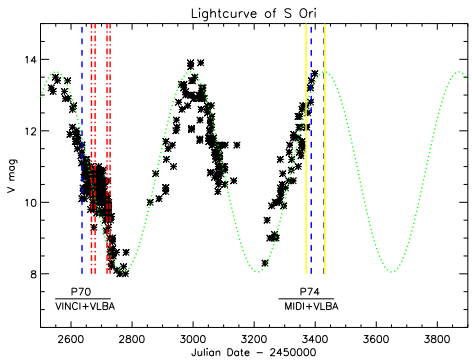

Fig. 4. Lightcurve of S Ori together with the epochs of our joint VLTI/VLBA measurements obtained so far. Note that the y-axis is given with increasing *V* magnitude, i.e. the stellar maximum is at the bottom and stellar minimum at the top. The study of S Ori was started in ESO period P70 (Dec. 2002/Jan. 2003) including near-infrared *K*-band VINCI and VLBA/SiO maser observations (Boboltz & Wittkowski 2005). In December 2004/January 2005, we obtained concurrent mid-infrared VLTI/MIDI and VLBA/SiO maser observations.

3. Joint VLTI/VLBA observations of the Mira star S Ori

We started our project of joint VLTI/VLBA observations of Mira stars in December 2002/January 2003 with coordinated near-infrared *K*-band VLTI/VINCI observations of the stellar diameter of the Mira variable S Ori and quasi-simultaneous VLBA observations of the 43.1 GHz and 42.8 GHz SiO maser emissions toward this star (Boboltz & Wittkowski 2005). We obtained in December 2004/January 2005 further concurrent observations including mid-infrared VLTI/MIDI observations to probe the molecular layers and the dust shell of S Ori, and new epochs of VLBA observations of the 43.1 GHz and 42.8 GHz SiO maser rings.

The December 2002/January 2003 represent the first-ever coordinated observations between the VLTI and VLBA facilities, and the results from these observations were recently published in Boboltz & Wittkowski (2005). Analysis of the SiO maser data recorded at a visual variability phase 0.73 show the average distance of the masers from the center of the distribution to be 9.4 mas for the $v = 1, J = 1 - 0$ (43.1 GHz) masers and 8.8 mas for the $v = 2, J = 1 - 0$ (42.8 GHz) masers. The velocity structure of the SiO masers appears to be random with no significant indication of global expansion/infall or rotation. The determined near-infrared, *K*-band, uniform disk (UD) diameters decreased from ∼ 10.5 mas at phase 0.80 to ∼10.2 mas at phase 0.95. For the epoch of our VLBA measurements, an extrapolated UD diameter of $\Theta^K_{\rm UD} = 10.8 \pm 0.3$ mas was obtained, corresponding to a linear radius of $R^K_{\rm UD} = 2.3 \pm 0.5$ AU or $R^K_{\rm UD} = 490 \pm 115\ R_\odot$. The model predicted difference between the continuum and *K*-band UD diameters is relatively low in the pre-maximum region of the visual variability curve as in the case of our observations (see above). At this phase of 0.73, the continuum diameter may be smaller than the *K*-band UD diameter by about 15% (Ireland et al. 2004). With this assumption, the continuum photospheric diameter for

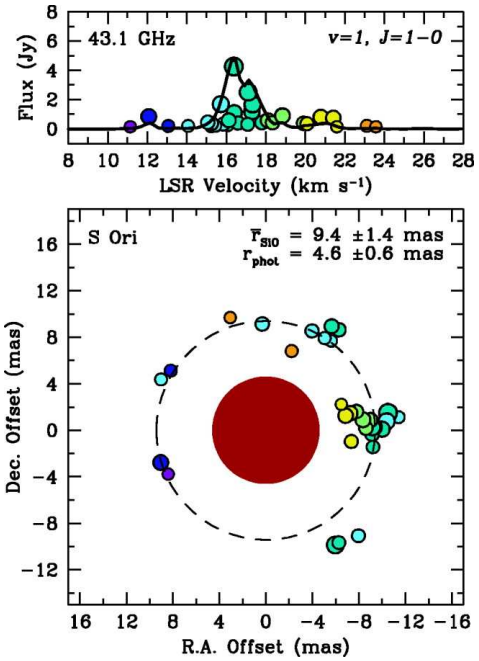

Fig. 5. First-ever coordinated observations between ESO's VLTI and NRAO's VLBA facilities: 43.1 GHz SiO maser emission toward the Mira variable S Ori measured with the VLBA, together with the near-infrared diameter measured quasi simultaneously with the VLTI (red stellar disk). From Boboltz & Wittkowski (2005).

the epoch of our VLBA observation would be $\Theta_{\rm Phot}$(VLBA epoch, phase = 0.73) $\approx$ 9.2 mas. Our coordinated VLBA/VLTI measurements show that the masers lie relatively close to the stellar photosphere at a distance of $\sim$2 photospheric radii, consistent with model estimates by Humphreys et al. (2002) and observations of other Mira stars by Cotton et al. (2004). The new 2004/2005 VLTI and VLBA data are currently being reduced and analyzed.

4. Outlook

We concentrate on a few stars in order to understand the CSE for a few sources in depth. In addition to the S Ori data described above, we have to date VLTI/MIDI observations of the supergiant AH Sco, and of the Mira star RR Aql, as well as concurrent VLBA observations for each of these targets/epochs. These data are currently being analyzed.

Further studies will aim at including more detailed near-infrared studies of the stellar atmospheric structure (close to the photosphere) employing VLTI/AMBER, concurrent with VLTI/MIDI and VLBA observations as discussed above. Making use of the spectro-interferometric capabilities of AMBER, and of the closure-phase information, these studies can in principle reveal horizontal surface inhomogeneities (see Wittkowski et al. 2002).

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