VLTI/AMBER observations of AGB stars – Investigating atmospheric molecular layers using spectro-interferometry

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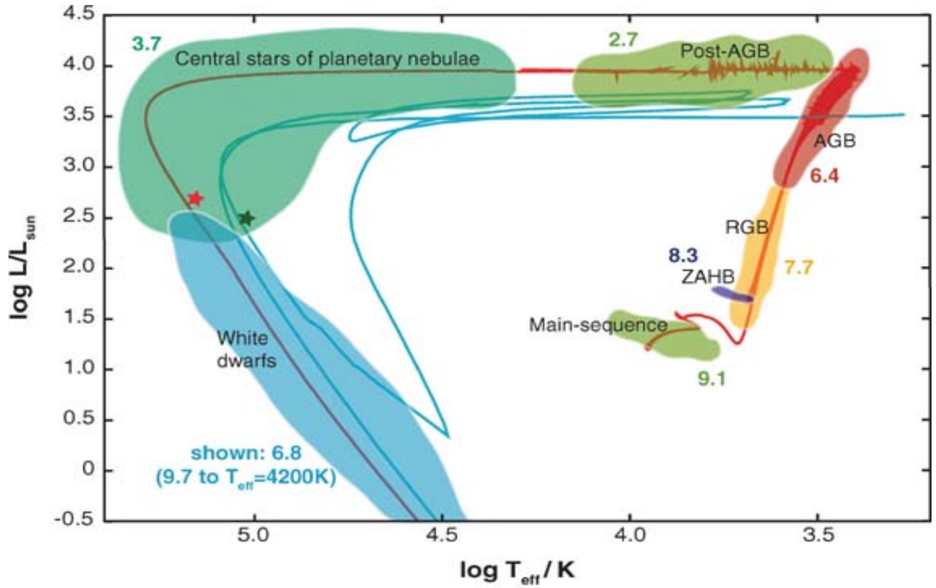
Two solar mass evolution track (Herwig 2005):



AGB stars represent the last stage of the evolution of low- to imtermediate mass stars that is driven by nuclear fusion. The most important driver for the further evolution is mass-loss, but which is purely understood, in particular for oxygen-rich stars.

MACHO observations of LMC red giants (Wood et al. 1999):

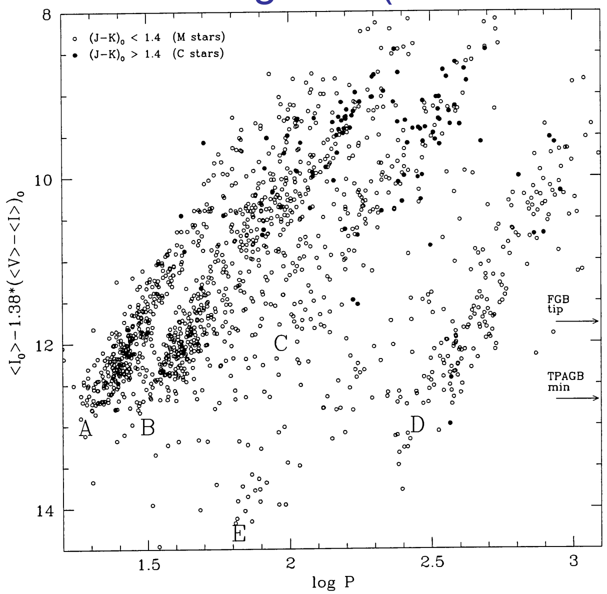


Figure 1. The period-luminosity relation for red variables. $<I>$ and $<V>$ are mean magnitudes, and P is in days. See text for details.

Basically all AGB stars are affected by stellar pulsations, starting with irregular pulsation in fundamental and mostly overtone modes on the low-luminosity AGB to regular pulsation in fundamental mode of Mira variables.

CODEX dynamic atmosphere models of Mira variables (Ireland et al. 2008, 2011):

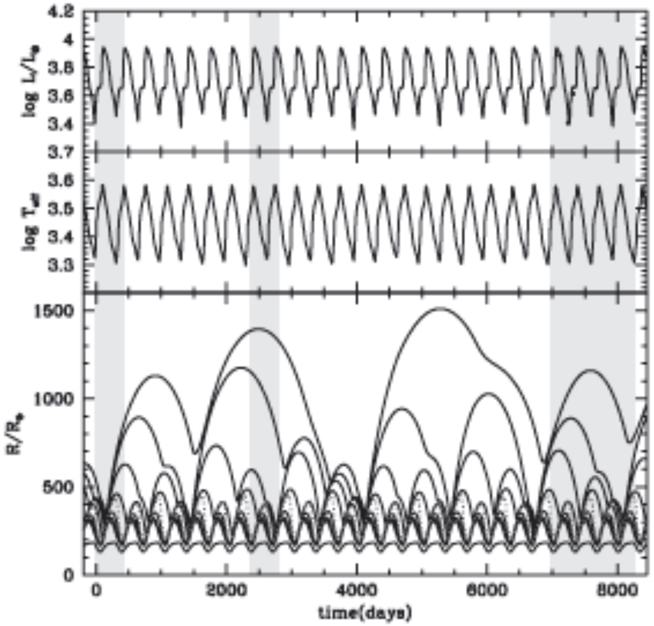
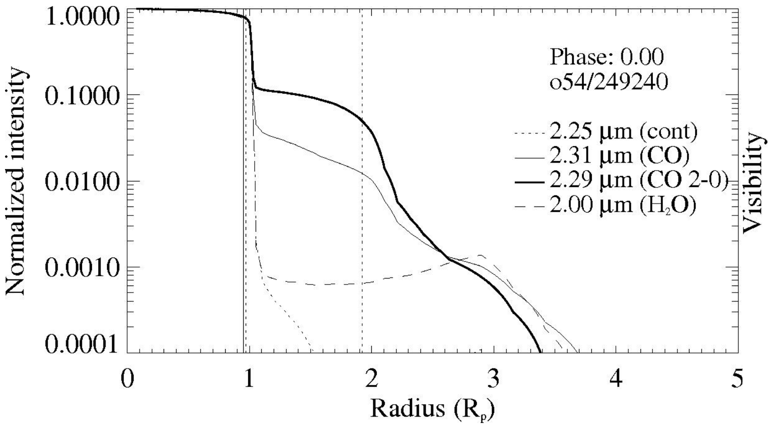
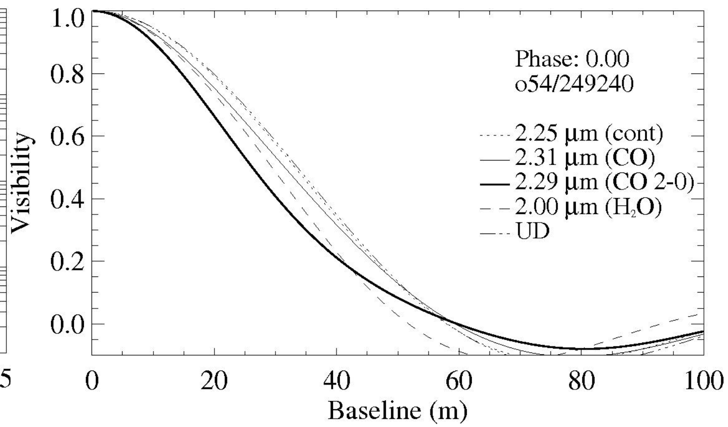


Figure 1. The luminosity (top panel), effective temperature (central panel) and radius of selected mass zones (lower panel) as a function of time for the *o54* pulsation model. The red dashed line in the bottom panel corresponds to the radius at Rosseland mean optical depth 2/3, and the effective temperature [$\propto (L/R^2)^{0.25}$] refers to this radius.

The pulsation in the stellar interior leads to atmospheric motion, which is regular near the Rosseland radius, but chaotic at mass zones further out (starting from 1.5-2 Rosseland radii).
See also already Icke et al. (1992).

This leads also to very complex and extended atmospheric intensity profiles with for example step-like shapes, and conditions favorable for the formation of molecules (for oxygen-rich stars most Importantly H_2O and CO).
Wavelength-dependent deviations from a uniform disk profile are predicted already in the first lobe of the visibility function.





Unveiling Mira stars behind the molecules(Perrin et al. 2004):

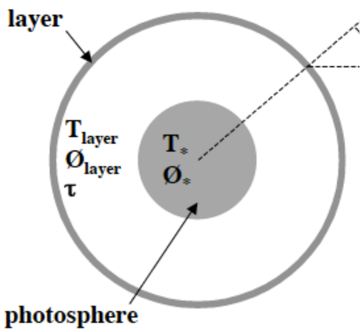
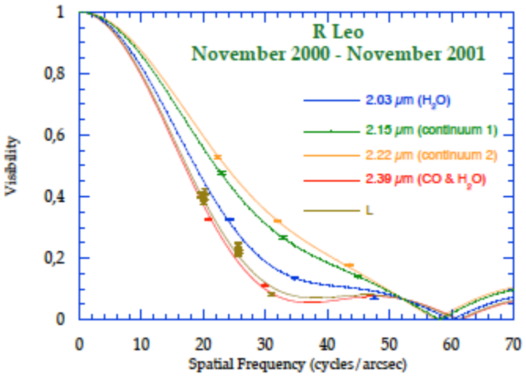


Fig. 2. Model of the star surrounded by a thin molecula
the angle between the radius vector and the line of sight
surface.



IOTA observations using a few narrow-band filters were successful to detect complex intensity profiles of molecular layers, and to model them with a toy model consisting of a central star and a thin molecular layer.

Asymmetric water shell of R Aqr (Ragland et al. 2006):

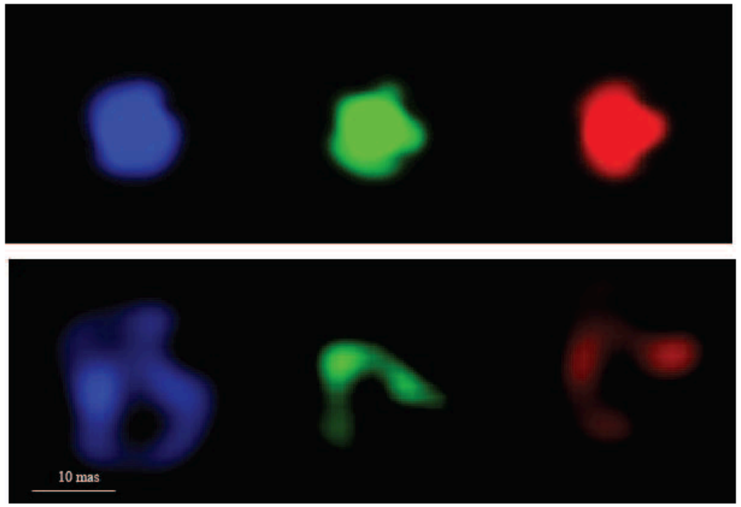
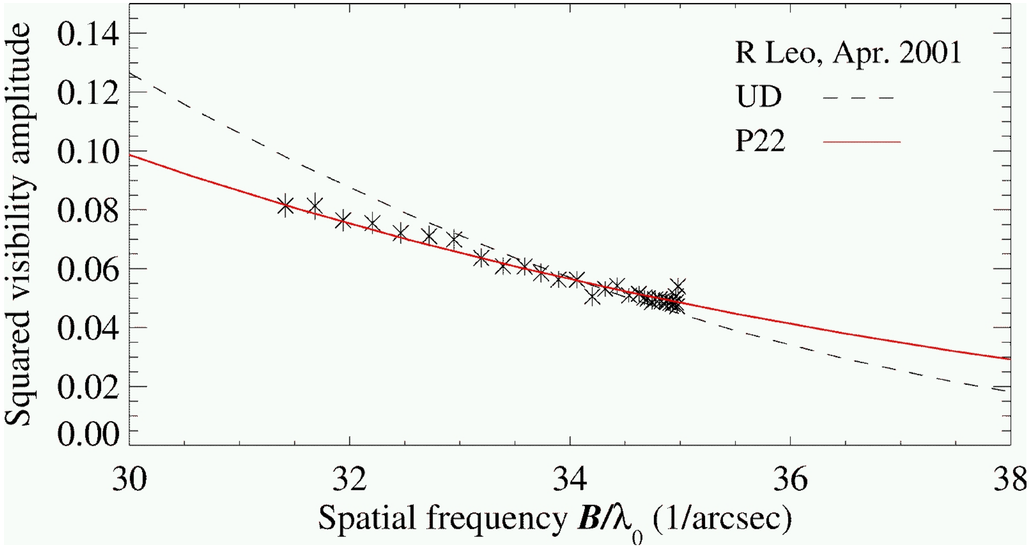
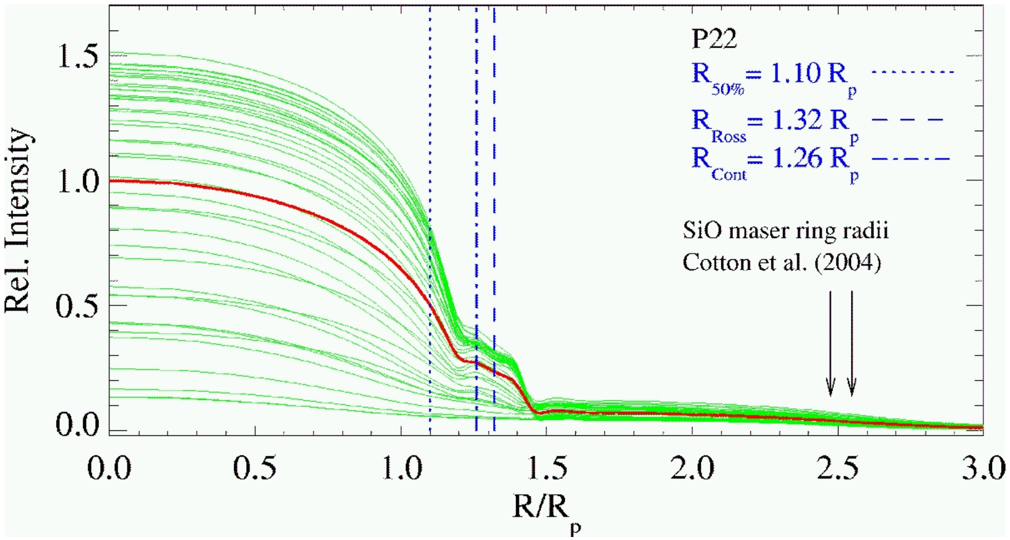


Fig. 9.—Reconstructed near-infrared images of R Aqr. The blue, green, and red color images (*from left to right*) represent 1.51, 1.64, and 1.78 µm respectively. The top row shows reconstructed images, and the bottom row shows primarily contributions from the shell, since we subtracted a Gaussian function from the reconstructed images to remove the stellar component. North is up, east to the left.

IOTA observations using broad- and narrow band filters were also successful to detect asymmetries.

VLTI/VINCI observations of R Leo (NIR K-band)



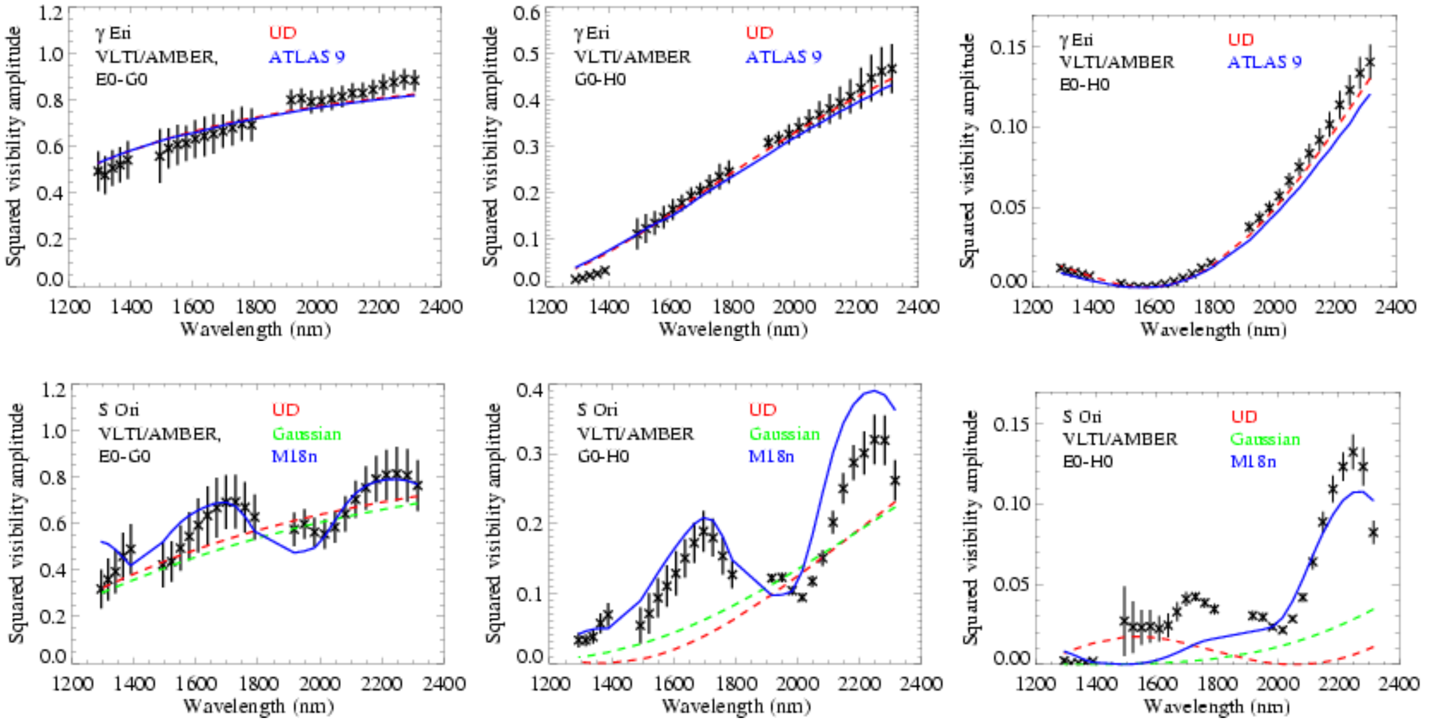


- Observations in April 2001 and January 2002 at stellar phases 0.08 and 1.02.
- Intensity profile is clearly different from a UD model already in the first lobe of the visibility function.
- Visibility is consistent with dynamic model atmospheres (P model by Ireland et al. 2004, predecessor of the CODEX models) that include effects from molecular layers.

See also Woodruff et al. 2004 for VLTI/VINCI observations of o Cet.

Fedele et al. 2005

LR AMBER observation of the Mira variable S Ori



M giant

Mira

The bumpy visibility curve is a signature of molecular layers lying above the photosphere.

At some wavelengths, the molecular opacity is low, we see the photosphere, the target appears smaller.

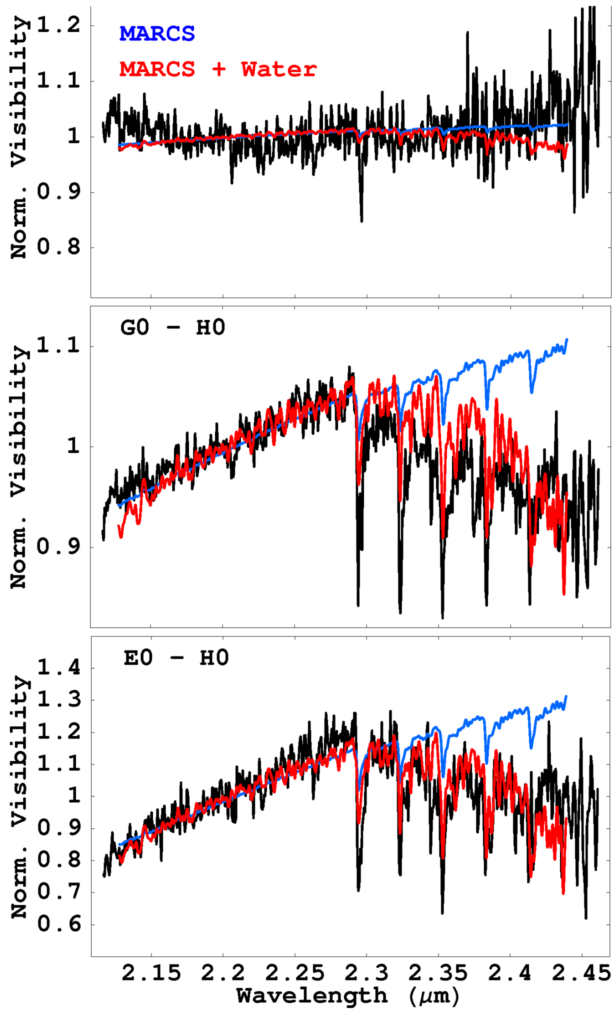
At other wavelengths, the molecular opacity is larger, we see the water shell, the target appears larger.

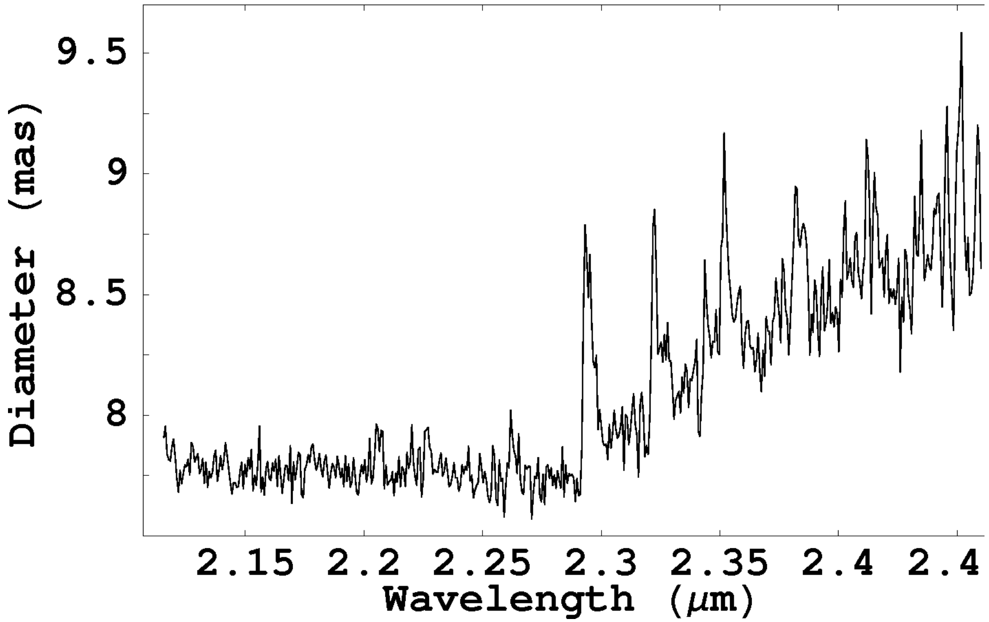
AMBER allows us to probe different layers of the extended atmosphere.

Visibility and UD diameter variations with wavelength resemble reasonably well the predictions by dynamic model atmospheres including molecular layers, in particular water vapor and CO.

Wittkowski, et al. 2008

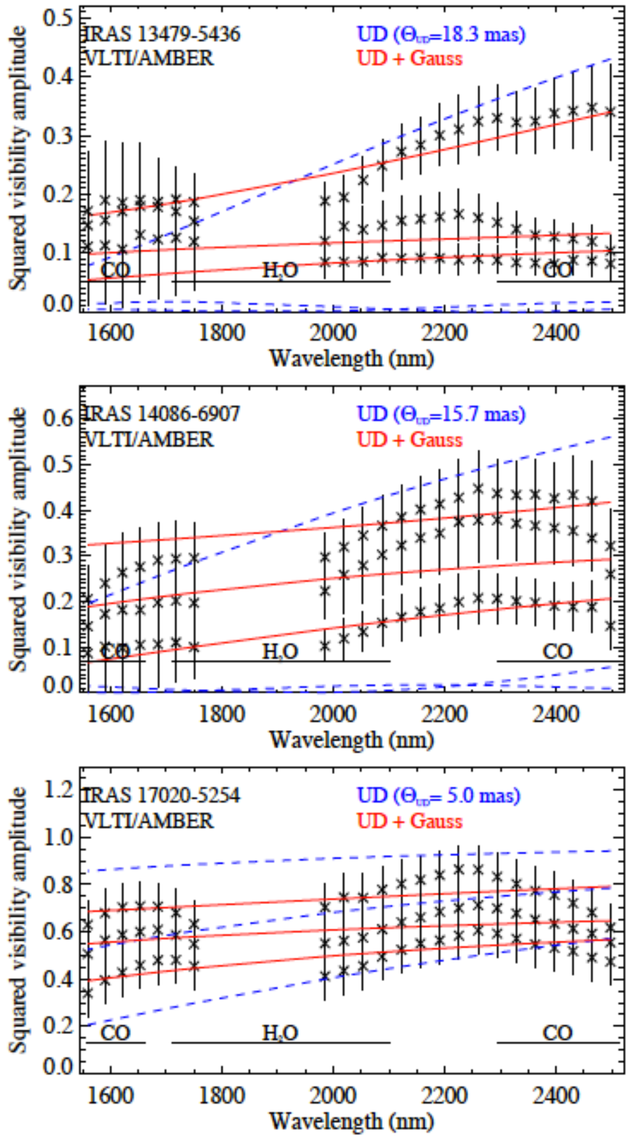
VLTI/AMBER MR observations of the semi-regular pulsating AGB star RS Cap





Marti-Vidal et al. 2011

VLTI/AMBER observations of three OH/IR stars



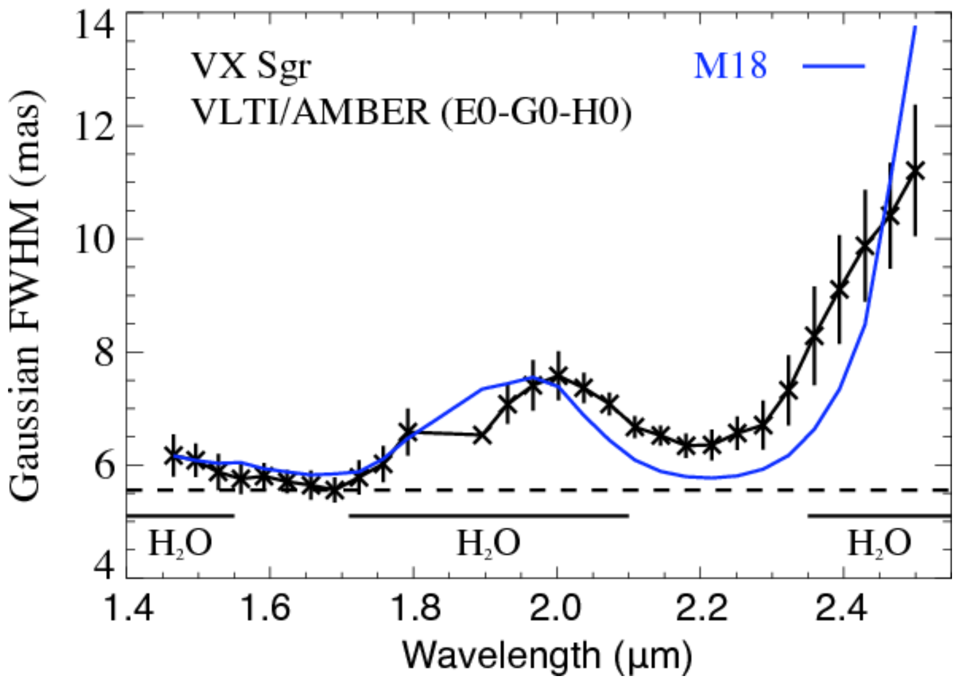
Detection of spectral visibility variations that resemble those of S Ori and other AGB stars and that coincide with the positions of CO and H_2O bands.

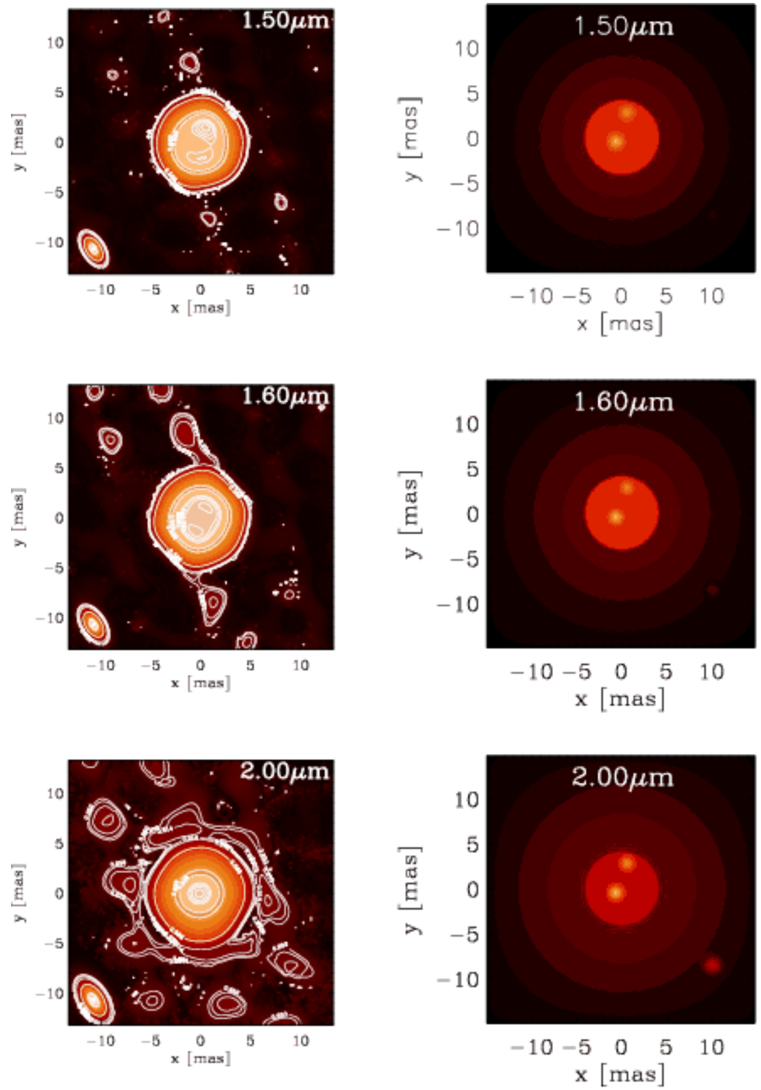
Single component model does not fit the data. Simple two-component model (UD+Gauss) results in stellar components of 3-5 mas (900-1400 R_{sun}) and CS dust shell components of 17-25 mas (9000-13000 R_{sun}), consistent with canonical properties of tip-AGB stars.

CS dust shell component is interpreted as the result Of the "superwind" phase. Different targets may represent different stages of the superwind and/or different stellar masses.

Ruiz-Velasco et al. 2011 (A&A, in press)

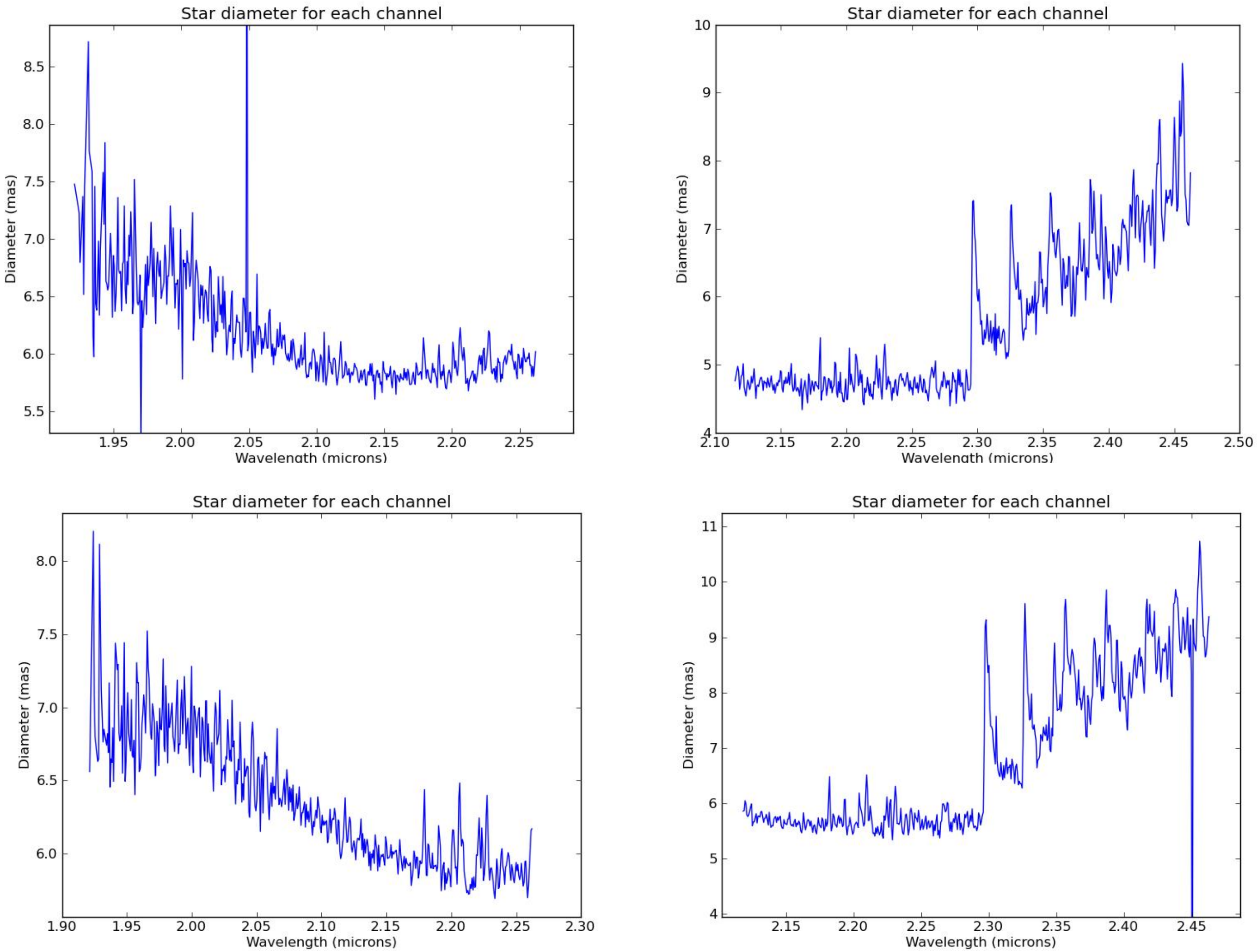
VLTI/AMBER observations of the supergiant (?) VX Sgr





Chiavassa et al. 2010

AMBER MR observations of red supergiants

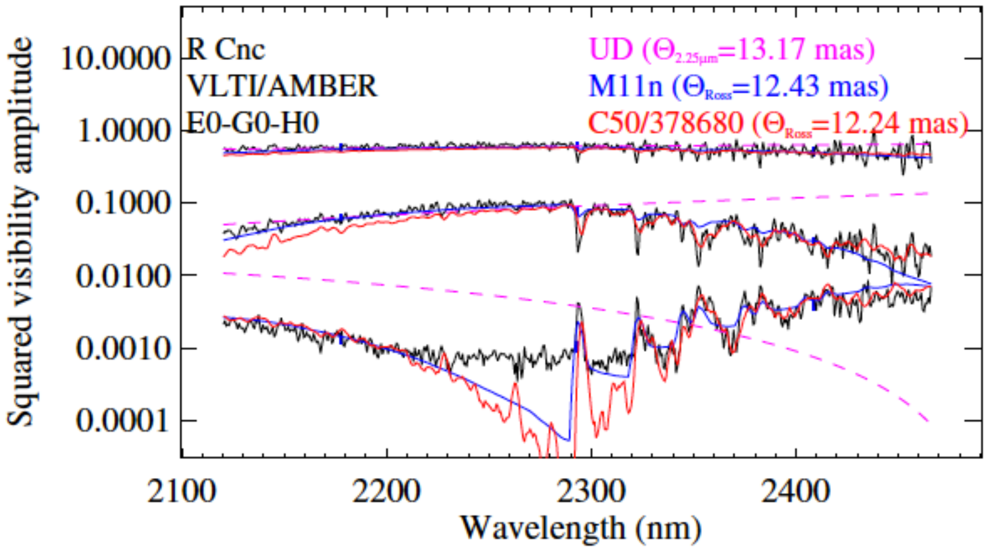


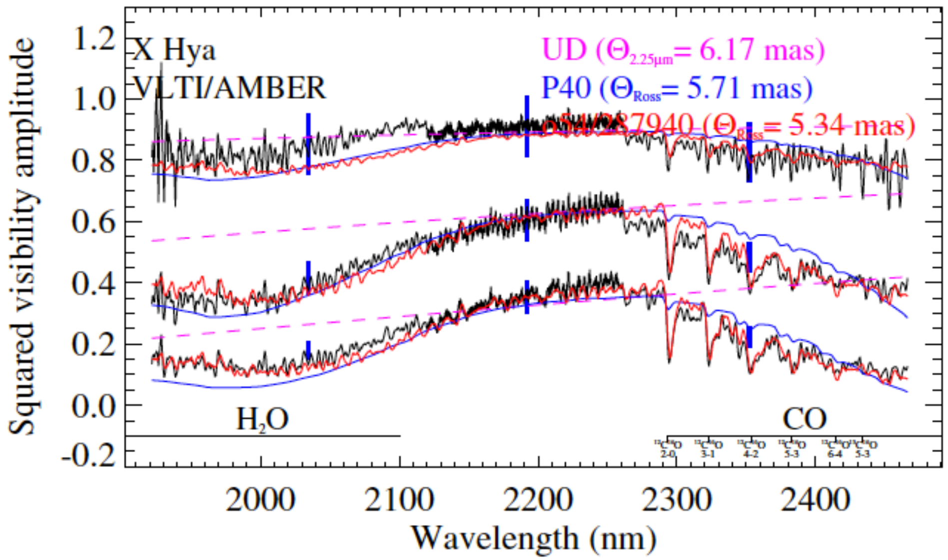
UY Sct

AH Sco

Arroyo et al, in preparation

Comparison of MR AMBER observations of Mira variables to new dynamic model atmospheres (CODEX models by Ireland, Scholz, & Wood 2008 and 2011

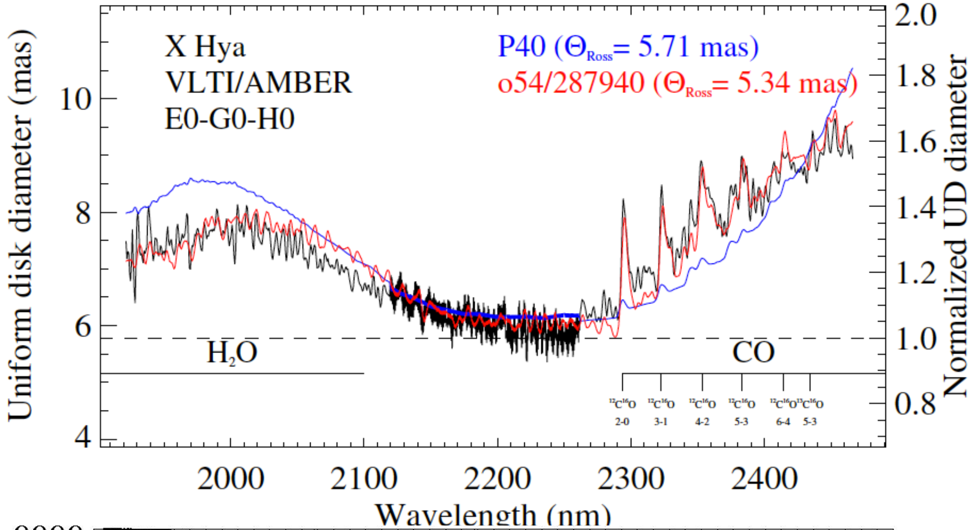




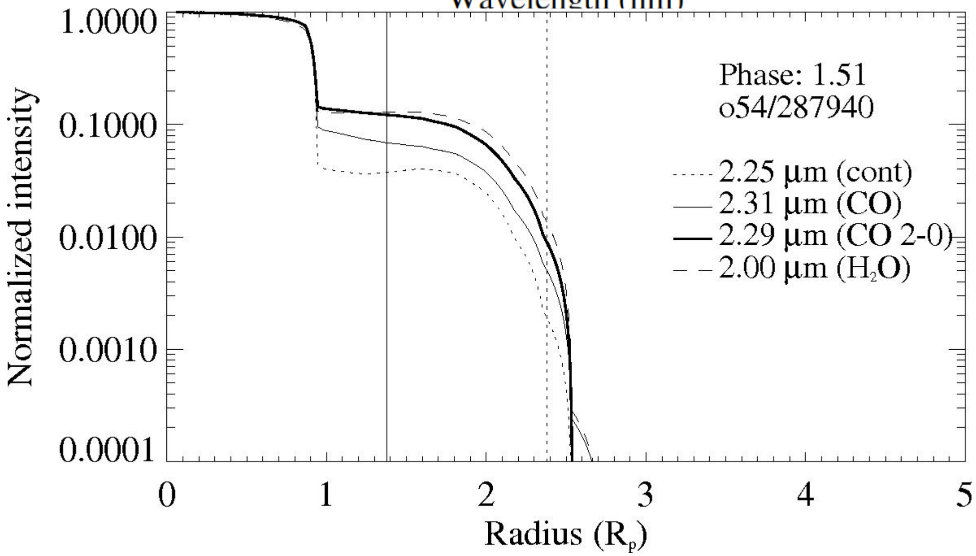
Visibilities are well consistent with predictions by the latest dynamic model atmosphere series based on self-excited pulsation models and including atmospheric molecular layers. Best-fit parameters (phase, T_{eff}, distances) consistent with independent estimates. Teff also determined from best-fit angular diameter and simultaneous SAAO photometry.

Wittkowski et al. 2011

Uniform disk diameter and intensity profiles



What does this mean ?



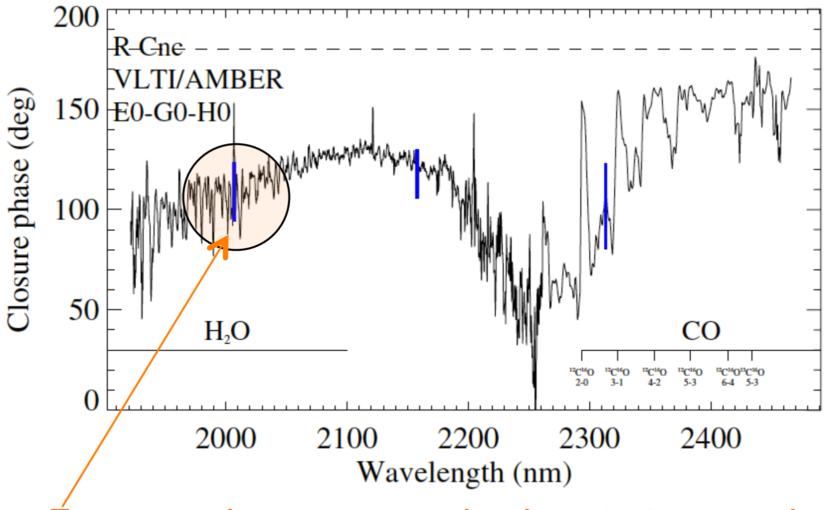
Nothing ?

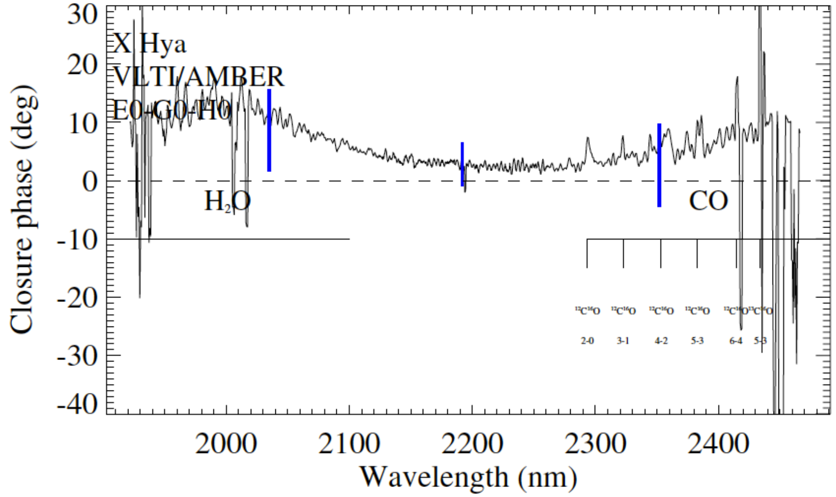
Some qualitative indication
of more intensity in outer layers ?

Where is the 'radius' ?

We are far beyond measuring "uniform disk" "radii" of stars.

Wavelength-dependent closure phases





For example, one unresolved spot at separation 4 mas contributing 3% of the total flux

Wavelength-dependent closure phases indicate deviations from point symmetry at all wavelengths and thus a complex non-spherical stratification of the atmosphere. In particular, the strong closure phase signal in the water vapor and CO bandpasses is interpreted as a signature of large-scale inhomogeneities/clumps of molecular layers.

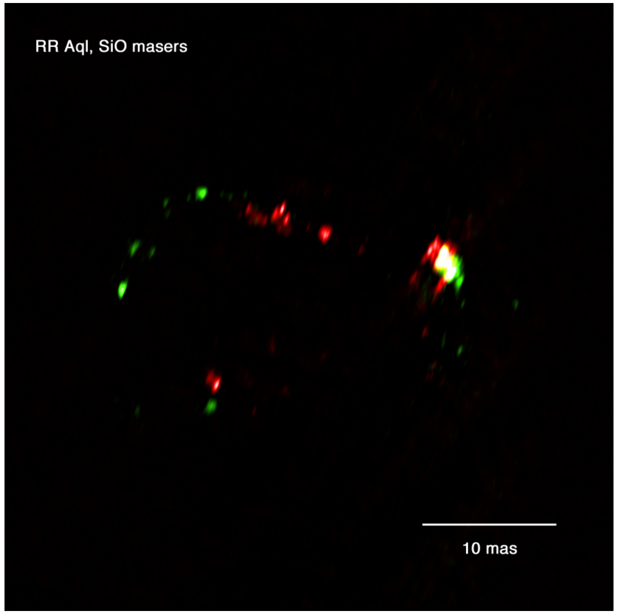
These might be caused by pulsation- and shock-induced chaotic motion in the extended atmosphere as theoretically predicted by Icke et al. (1992) and Ireland et al. (2008, 2011).

May be important for non-LTE chemistry and the origin of asymmetric CSE shapes.

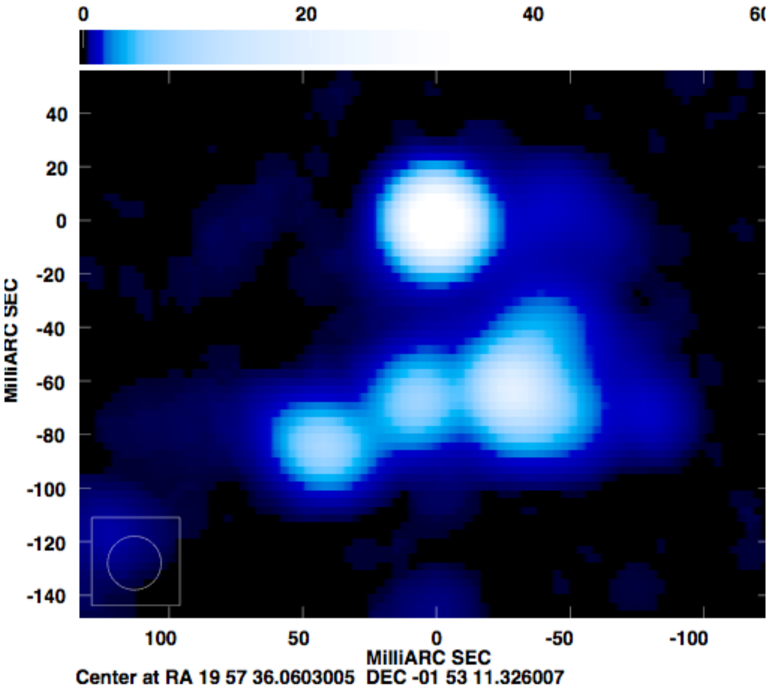
Wittkowski et al. 2011

Tracing molecular layers outward using masers

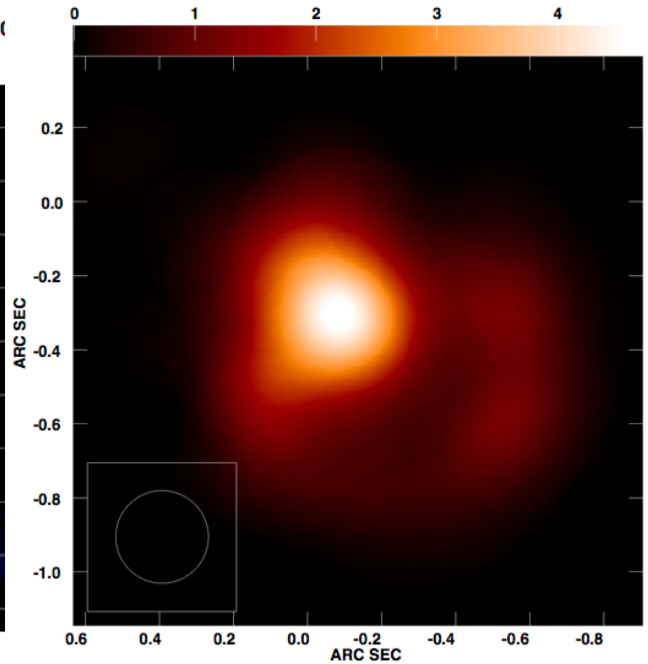
SiO (VLBA)



H_2O (MERLIN)



OH (MERLIN)



Preliminary rough radial structure (different epochs !):

R_* ~ 7.6 mas

R_{SiO} ~ 12x25 mas ~ 1.6x3.3 R_*

R_{H2O} ~ 120x120 mas ~ 16x16 R_*

R_{OH} ~ 800x800 mas ~ 100 x 100 R_*

R_{sil} ~ 30 mas ~ 4 R_*

Summary

- AMBER spectro-interferometry has proven to be a valuable new tool to investigate the complex atmospheric structure of AGB stars including atmospheric molecular layers.
- Atmospheric molecular layers are a common phenomenon of AGB stars of very different luminosities and mass-loss rates alike (SRV, Miras, OH/IR stars), and even extend to massive evolved stars.
- Observations of Mira variables are consistent with the latest dynamic model atmosphere series based on self-excited pulsation models and opacity-sampling radiation treatment (CODEX series by Ireland, Scholz & Wood).
- Closure phases indicate deviations from point symmetry at all wavelengths and thus a complex non-spherical stratification of the atmosphere.
- The deviation from point symmetry appears stronger at molecular bands originating at outer layers, which may be caused by pulsation- and shock induced chaotic motion (different extensions of certain mass zones at different sides of the star).
- Clumpy atmospheric molecular layers may be important for non-LTE chemistry and as the source of asymmetric shapes of the CSE at larger distances.
- To come: Model-independent imaging at high spectral resolution, intra-cycle and cycle-to-cycle variability, coordinated observations with other facilities (VLBA, ALMA), shock front positions, …