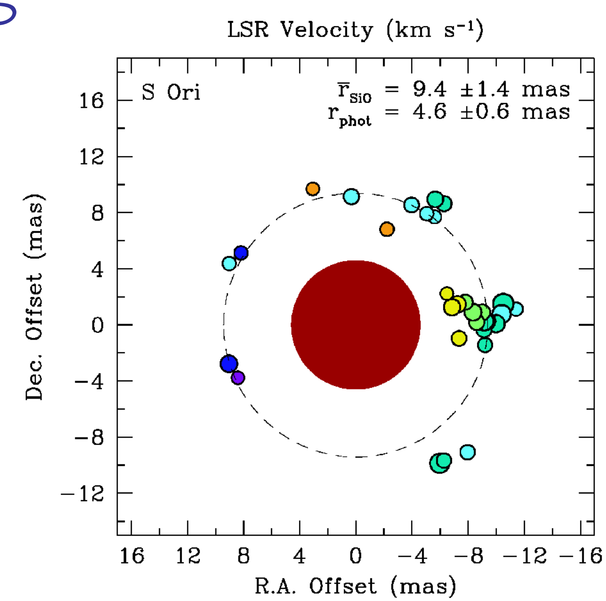
Multi-wavelength interferometry of evolved stars



Markus Wittkowski (ESO)

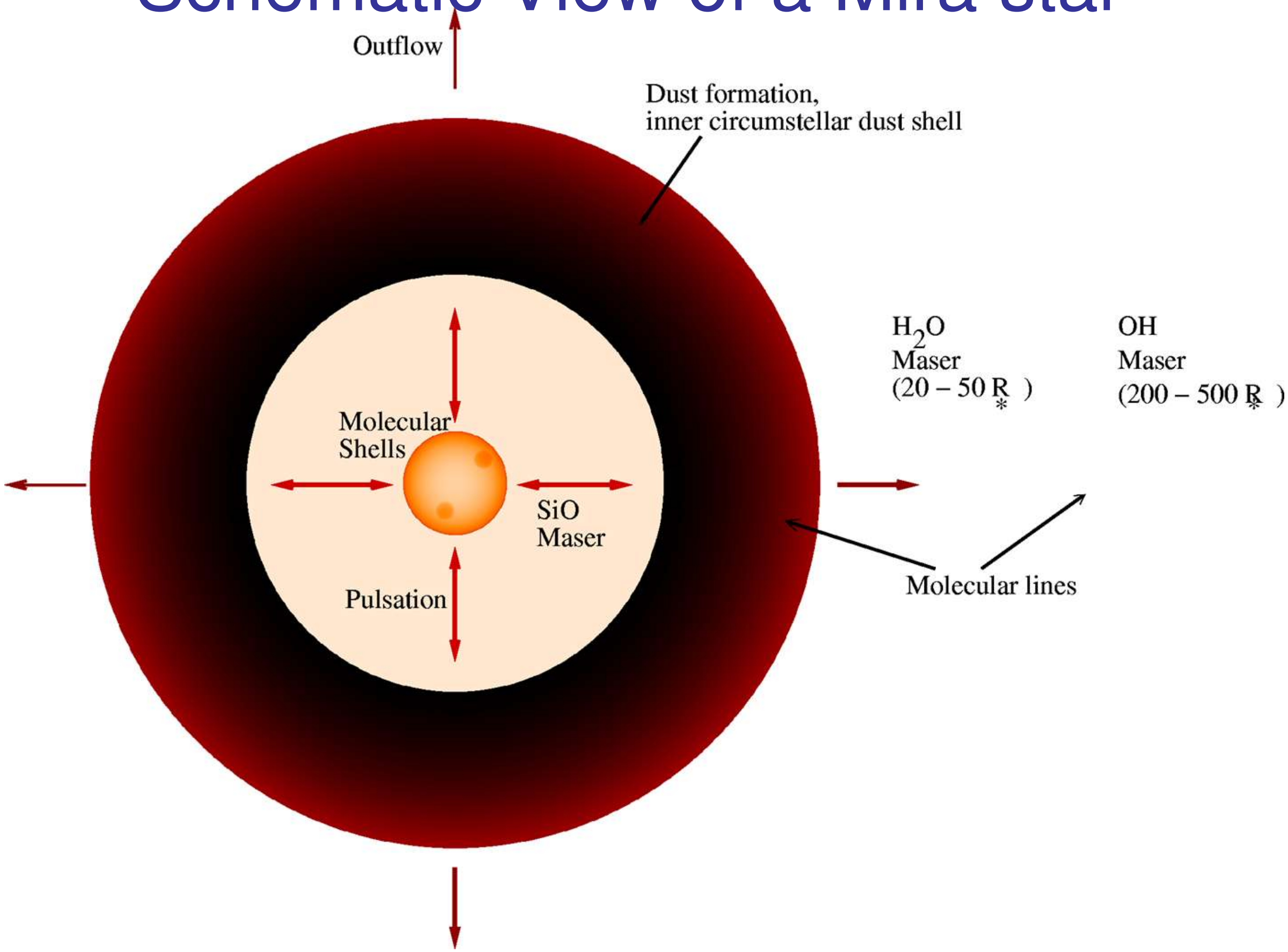
Main collaborators:

VLTI/VLBA project: David A. Boboltz (USNO),
Thomas Driebe, Keiichi Ohnaka (MPIfR)

Stellar atmospheres: Jason Aufdenberg (NOAO), Christian Hummel (ESO),
Michael Scholz (ITA)

USNO, Scientific Colloquium, 1 September 2005

Schematic View of a Mira star



Detailed structure of atmosphere and CSE ?

Detailed physics of the mass-loss process ?

VLTI (AMBER & MIDI):

- Size and shape of IR and MIR photosphere.
- CLV, effects by molecular layers, inhomogeneities.
- Size, chemistry, shape of the warm dust shell.

VLBA:

- SiO maser zone: size, shape, kinematics.
- Radio photosphere.
- Water and OH maser at larger distances.

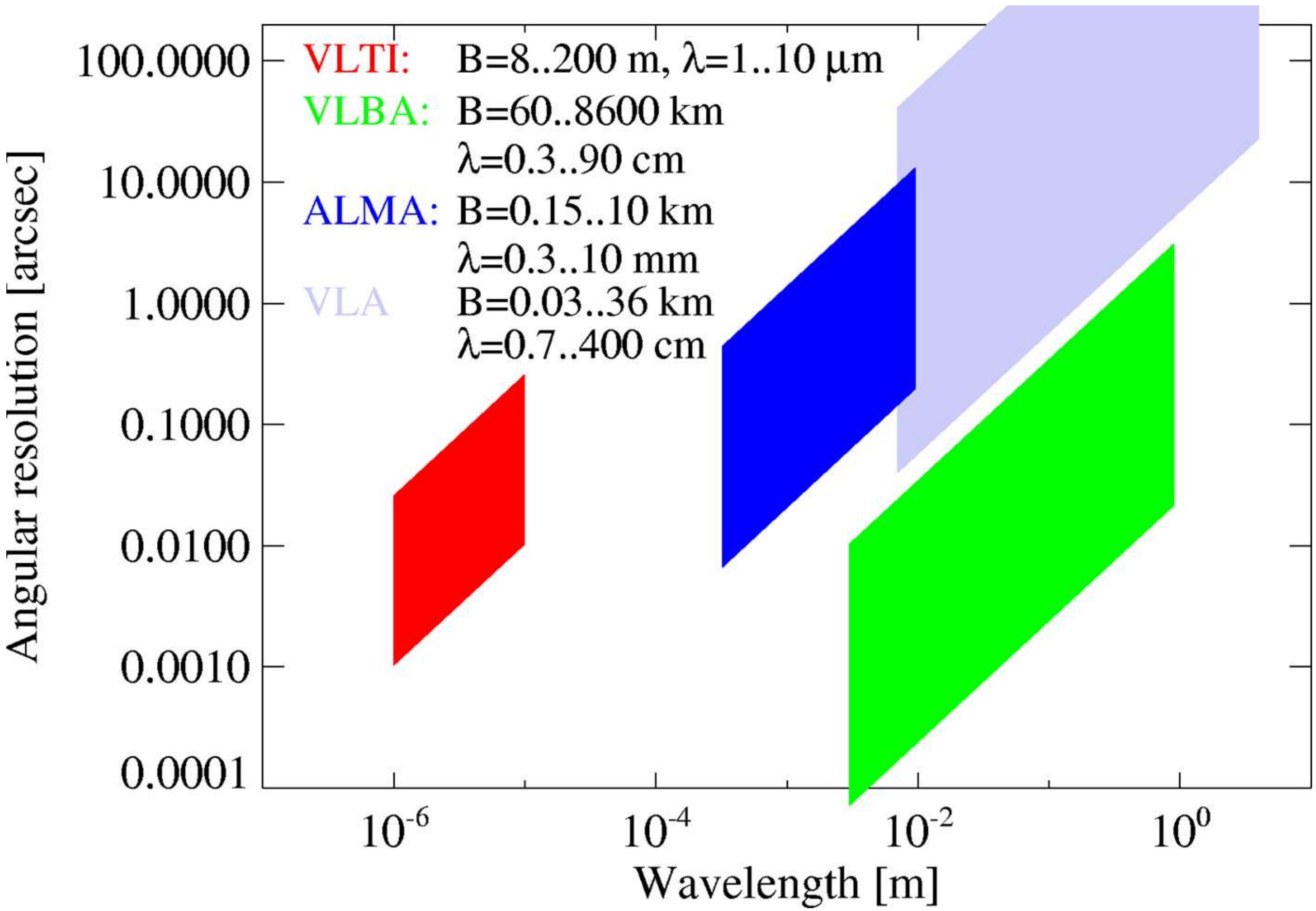
ALMA:

- mm Photosphere.
- Cool dust.
- High-fidelity images.
- Molecular bands / maser.

Other facilities:

- Parallaxes.
- Bolometric fluxes.
- High-resolution spectra.
- Outer envelope(Speckle/AO).

Comparison of VLTI, VLBA, and ALMA

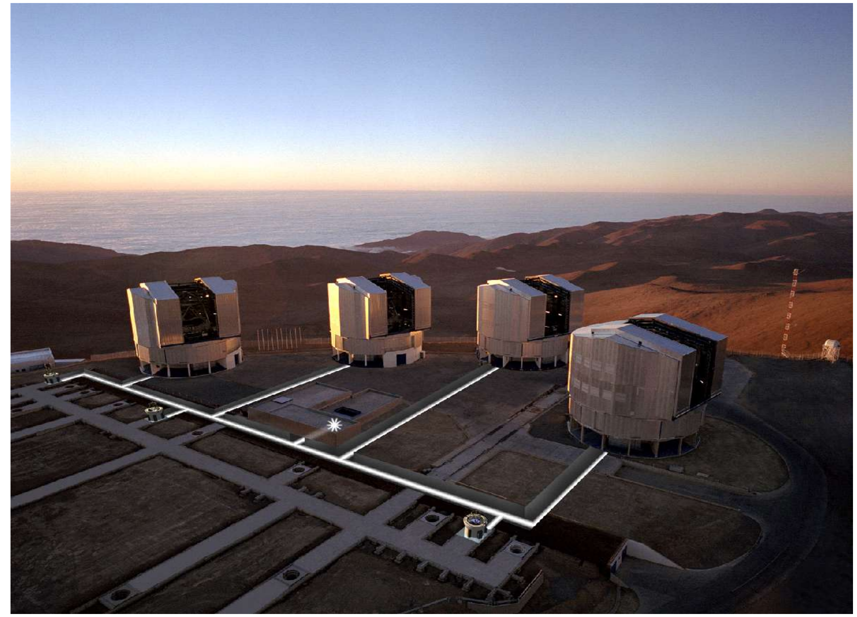


- VLTI, VLBA, and ALMA can observe the same targets in terms of angular resolution and sensitivity.
- They provide complementary information on different components and regions.

<u>Telescopes</u>:
VLTI : 4 x 8m + 4 x 1.8 m
VLBA : 10 x 25 m
ALMA : 64 x 12 m
VLA : 27 x 25 m

The ESO VLT Interferometer

- Four fixed 8-m Unit Telescopes (UTs). Max. Baseline 130m.
- Three (four) 1.8-m Auxiliary Telescopes (ATs), relocateable on 30 different stations.
  Baselines 8 – 200m.
- Near-infrared (J, H, K) closure-phase instrument AMBER. Spectral resolutions 35, 1500, 10000.
- Mid-infrared 8-13 μm 2-beam instrument MIDI. Spectral resolutions 30, 230.
- Dual feed phase referencing (PRIMA).



AT1 and AT2 with Open Domes

ESO PR Photo 07b/05 (14 March 2005)

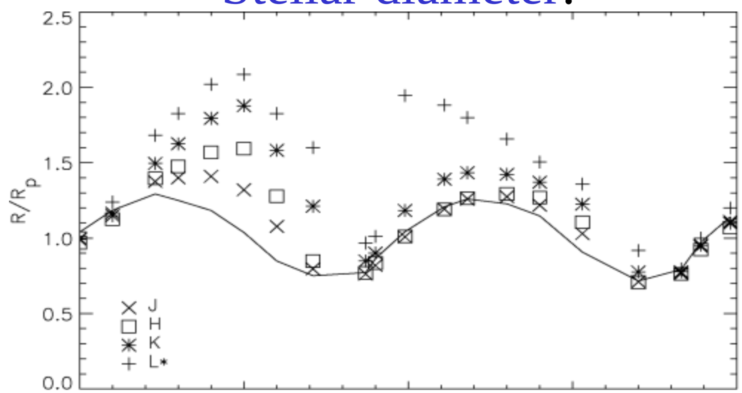
Maser observations with the VLBA

- The VLBA is a system of 10 25m radio telescopes; 0.3-90 GHz, angular resolution down to sub-milli-arcsecond.
- SiO, OH, H_2O, maser emission toward evolved stars can well be spatially resolved.
- Maser radiation appears in maser spots of sizes 10^13-10^16 cm, each with its own well-defined velocity; related to molecular clouds of common velocity with certain temperature and density conditions.
- Each spot emits beamed radiation to the observer.
- SiO masers are tangentially amplified with respect to the stellar radiation, leading to ring-like structures.

Variation with phase of stellar diameters and SiO maser shell radii of Mira stars

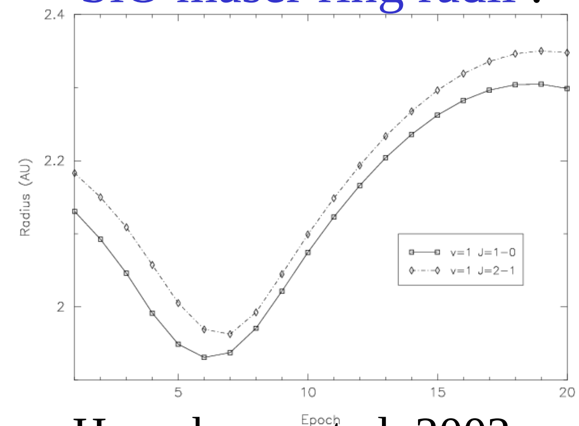
Stellar diameter:

Theory:



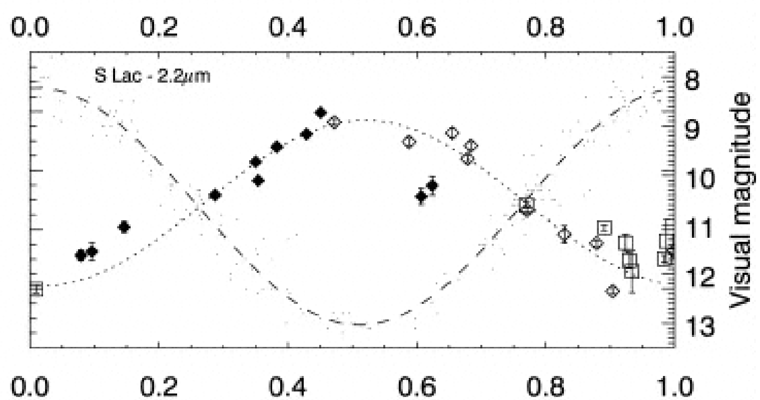
Ireland, Scholz, & Wood 2004

SiO maser ring radii :

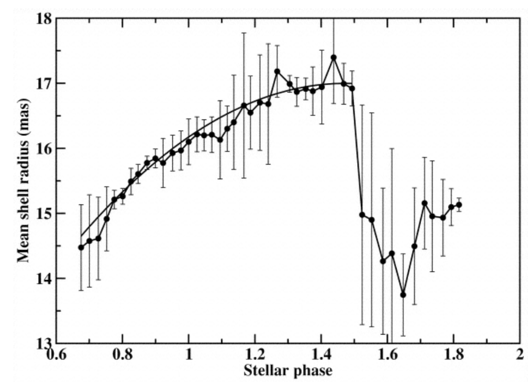


Humphreys et al. 2002

Observations:



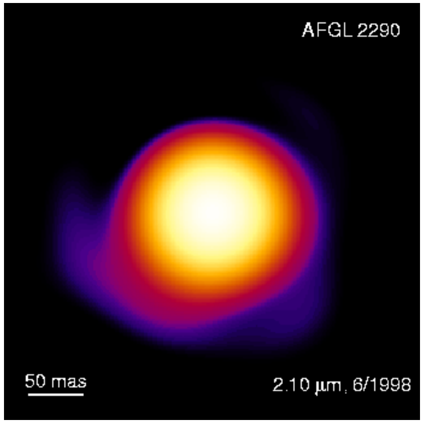
Thompson et al. 2002



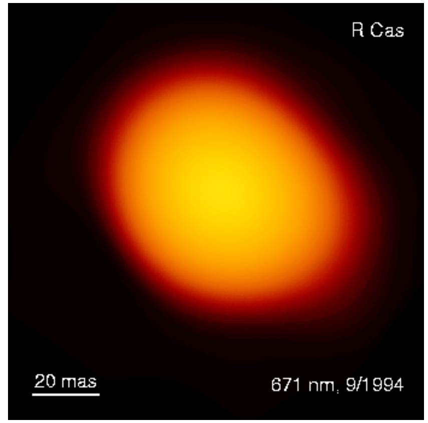
Diamond & Kemball 2003

=> Contemporaneous observations of stellar diameters and SiO maser shell!

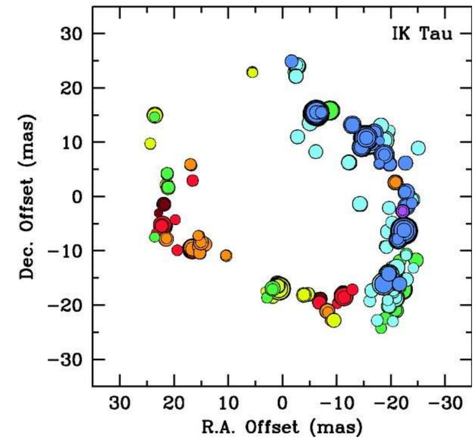
From spherically symmetric AGB stars to axisymmetric/bipolar Planetary Nebulae ?



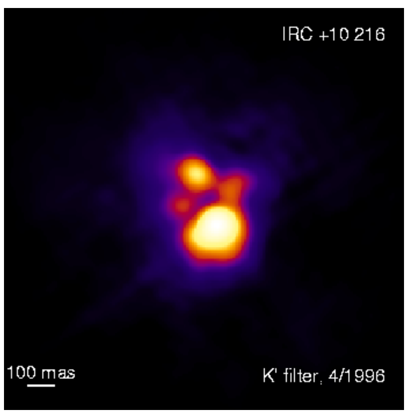
Oxygen-rich AGB star AFGL 2290
Gauger et al. 1999



Mira star R Cas in TiO absorption.
Weigelt et al. 1996

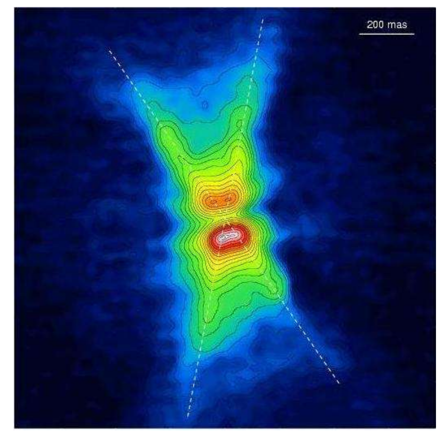


SiO maser shell around the Mira star IK Tau
Boboltz & Diamond 2005



Carbon-star IRC+10216
Weigelt et al. 1998

Cat's Eye Nebula (PN)
HST Image Archive

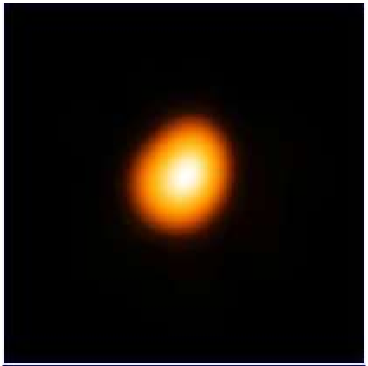


Red Rectangle
Tuthill et al. 2002

Optical/ NIR

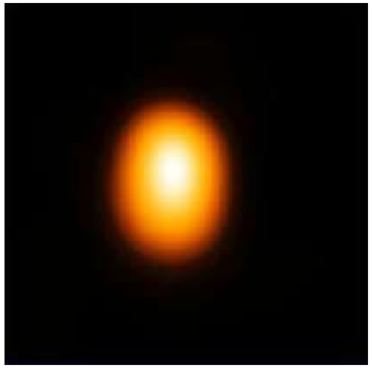
From red supergiants to WR stars: VY CMa

RG 780



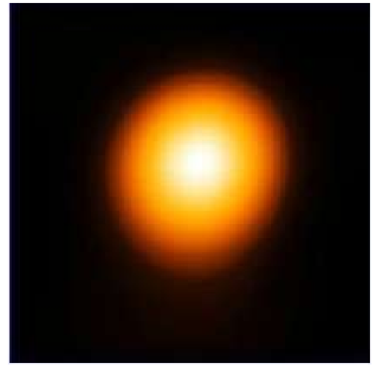
67x83 mas
100x125 AU

1.28 μm



80x116 mas
120x174 AU

2.17 μm

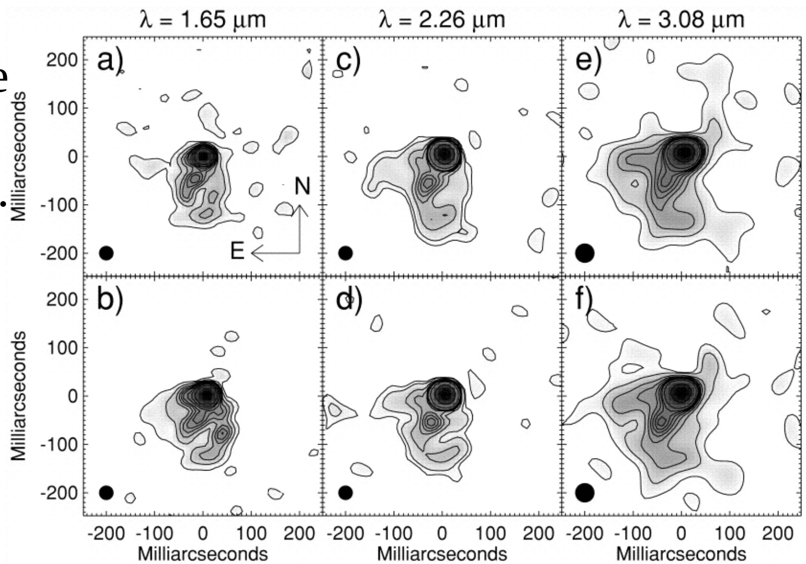


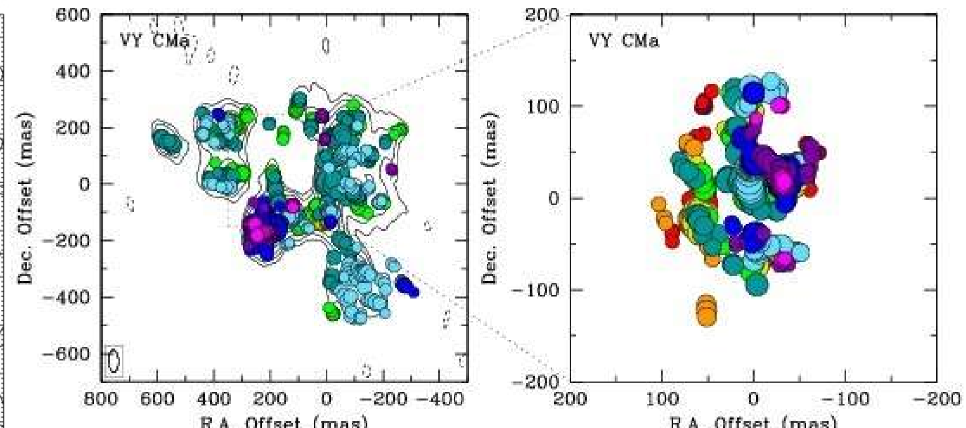
138x205 mas
207x308 AU

Images reconstructed by bispectrum speckle Interferometry.

Wittkowski et al. 1998

Keck aperture masking. Monnier et al. 1999





SiO maser emission, ground state, and first excited state. Boboltz 2005.

Summary of the introduction/ Scientific questions

- Fundamental stellar parameters (R, T, M).
- Structure/relative distances of the different regions of the stellar atmosphere and the circumstellar environment.
- Variation of this structure as a function of stellar variability.
- Kinematics of the circumstellar environment. Rotation, infall/expansion ?
- Evolution from symmetric stars to axisymmetric/bipolar Planetary Nebulae ?
- Coordinated multi-wavelength approach is promising.

Visual to infrared interferometry:

- Center-to-limb intensity variations (CLVs) across the stellar disks.

  Measure of the vertical temperature profile of the stellar atmosphere (limb-darkening effect). Predicted by theoretical stellar atmosphere models. Can be observed by visual/near-infrared interferometry.
- Surface features such as spots.

  Horizontal temperature inhomogeneities. Requires phase information/ imaging capabilities.
- Molecular layers close to continuum-forming layers.

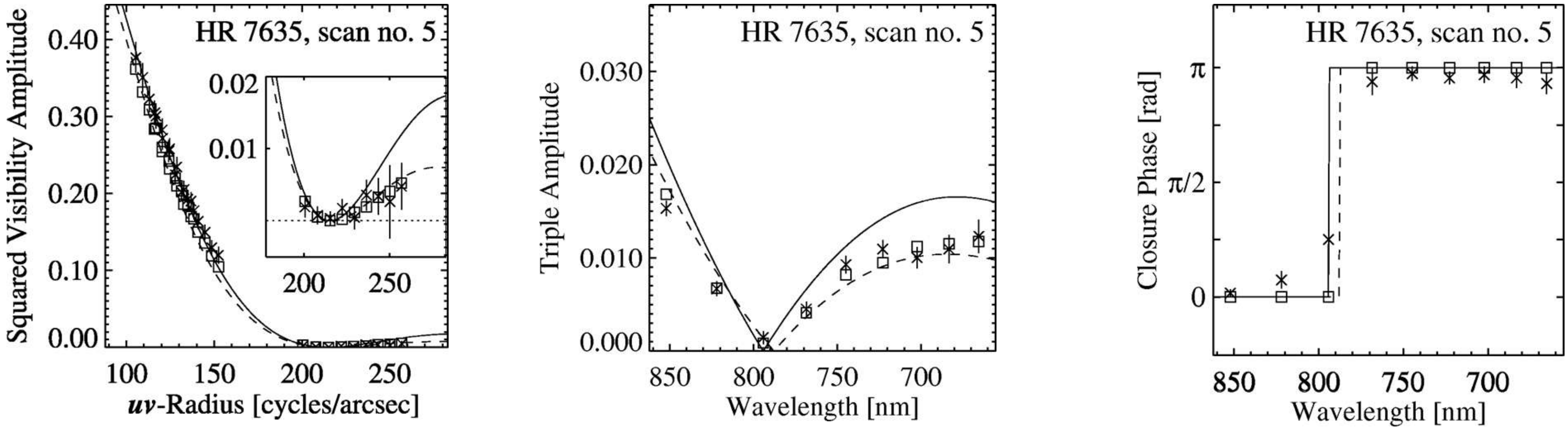
  Leads to complex, e.g. two-component, CLVs. Can be observed similar as pure limb-darkening observations.
- Dust shells

  Mid-infrared interferometry.

ESO

Optical

Intensity profiles: NPOI observations of Gam Sge (M0III)

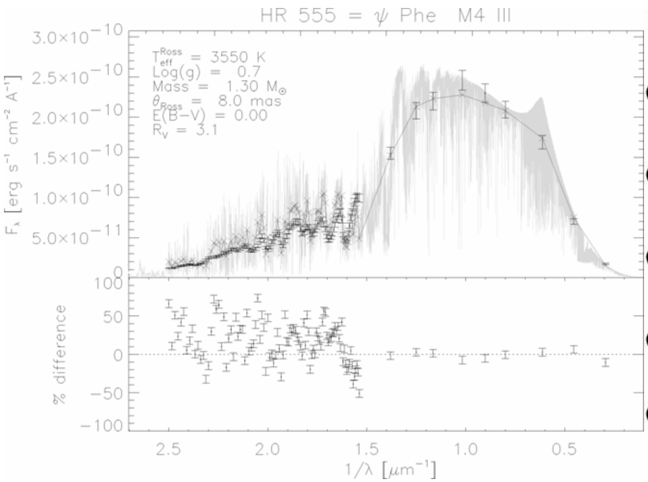


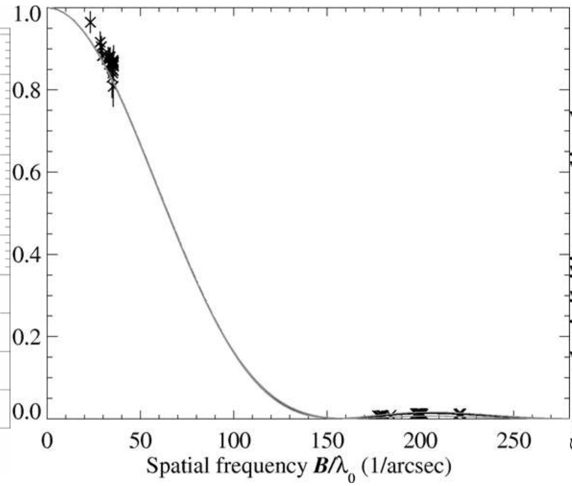
- Multi-wavelengths in the optical
- Limb-darkening probed by monochromatic intensity profiles *and* wavelength dependence (similar to AMBER's potential)
- Constraints of model atmosphere parameters succeeded.

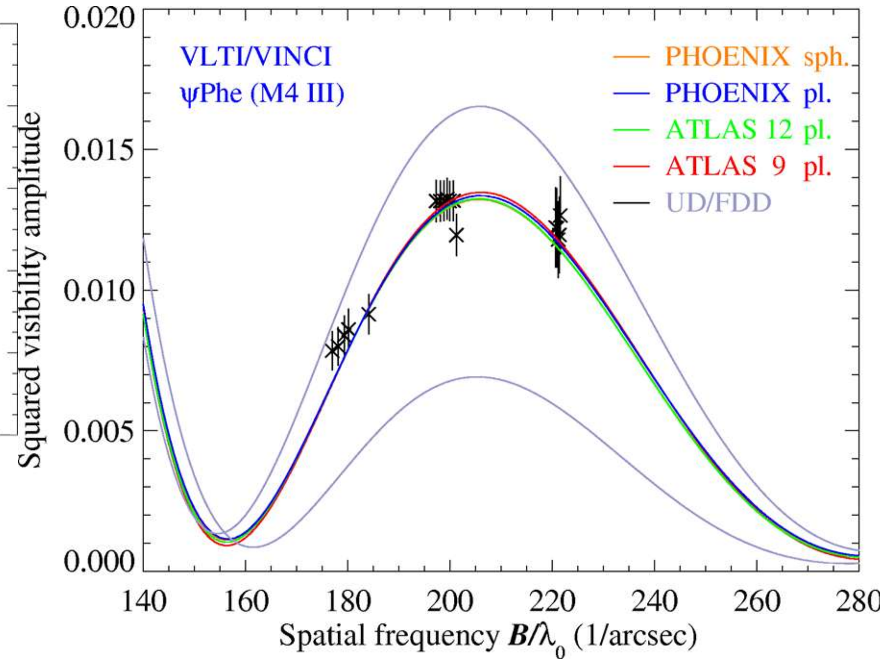
log g / T_{eff}	0.0	0.5	1.0	1.5	2.0	2.5
3500	1.50	1.40	1.35	1.38	1.47	1.58
3750	1.29	1.29	1.29	1.29	1.27	1.26
4000	1.18	1.17	1.17	1.17	1.18	1.18
4250	1.20	1.20	1.19	1.19	1.19	1.19
4500	1.26	1.25	1.24	1.23	1.23	1.23

Wittkowski et al. 2001

Intensity profiles: VLTI observations of Psi Phe (M4III)

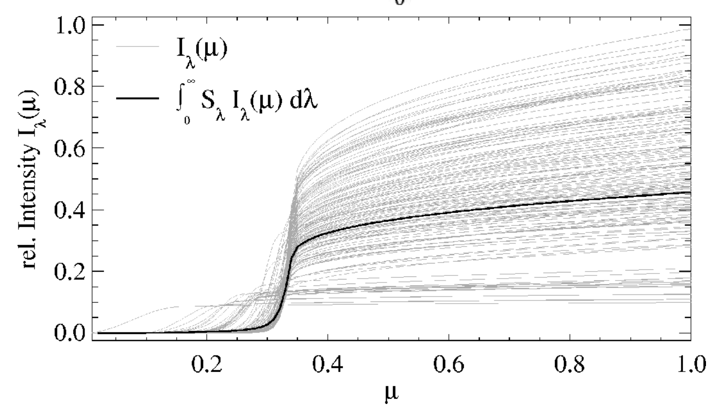






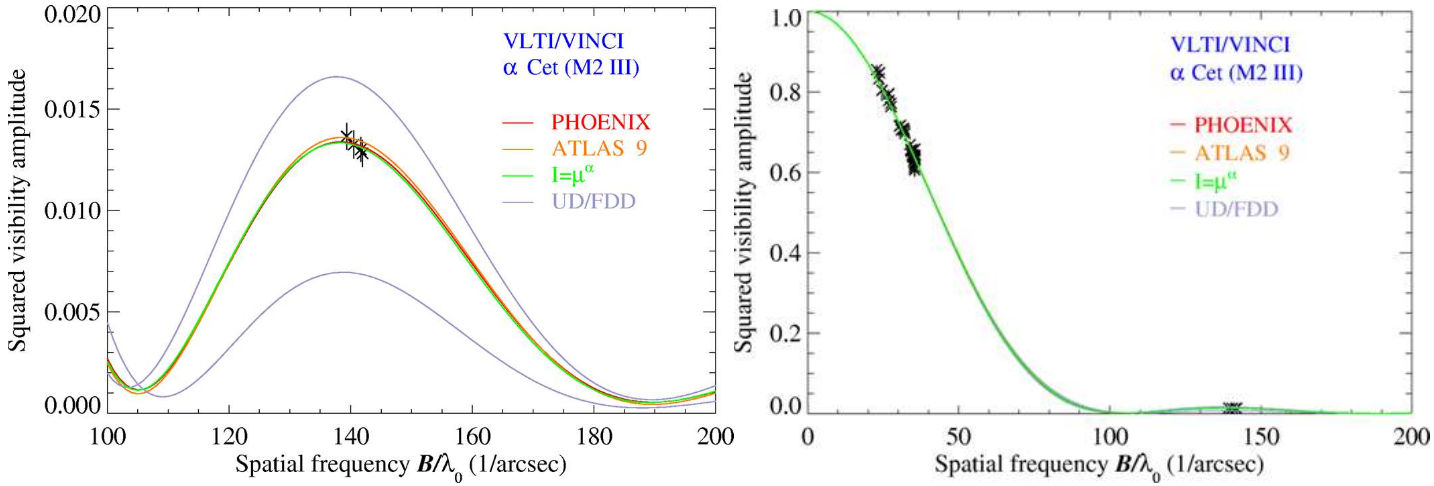
Broad-band VLTI/VINCI observations of the limb-darkening of Psi Phe succeeded in 2001.

Atmosphere models, as constrained by comparison to spectrophotometry, predict a limb-darkening curve that is consistent with the VINCI data.

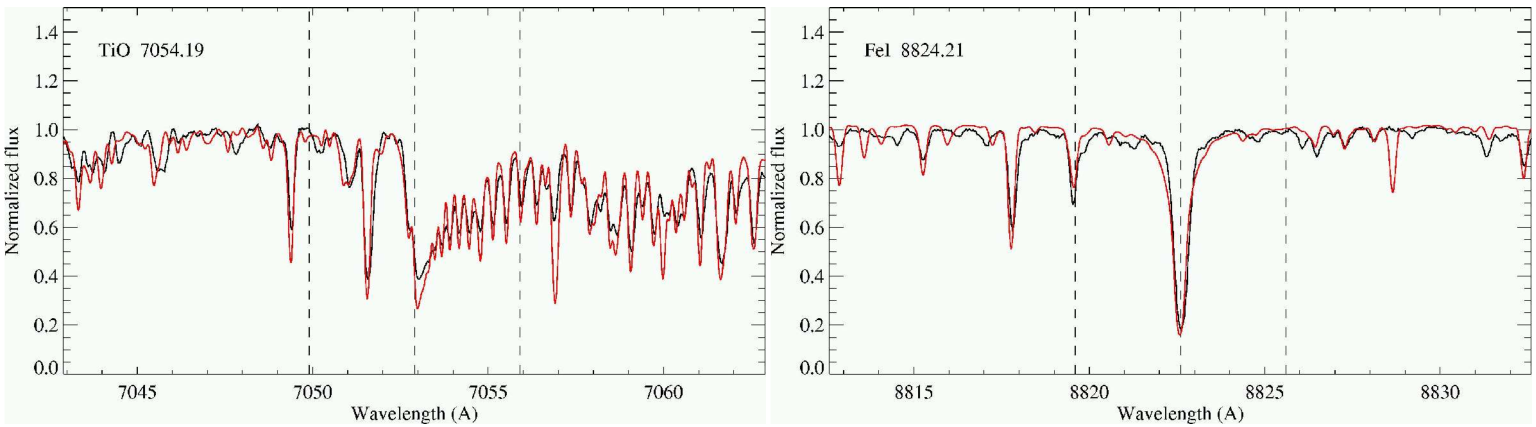


Wittkowski et al. 2004

UVES and VINCI observations of Alpha Ceti (M2 III)



VLTI/VINCI



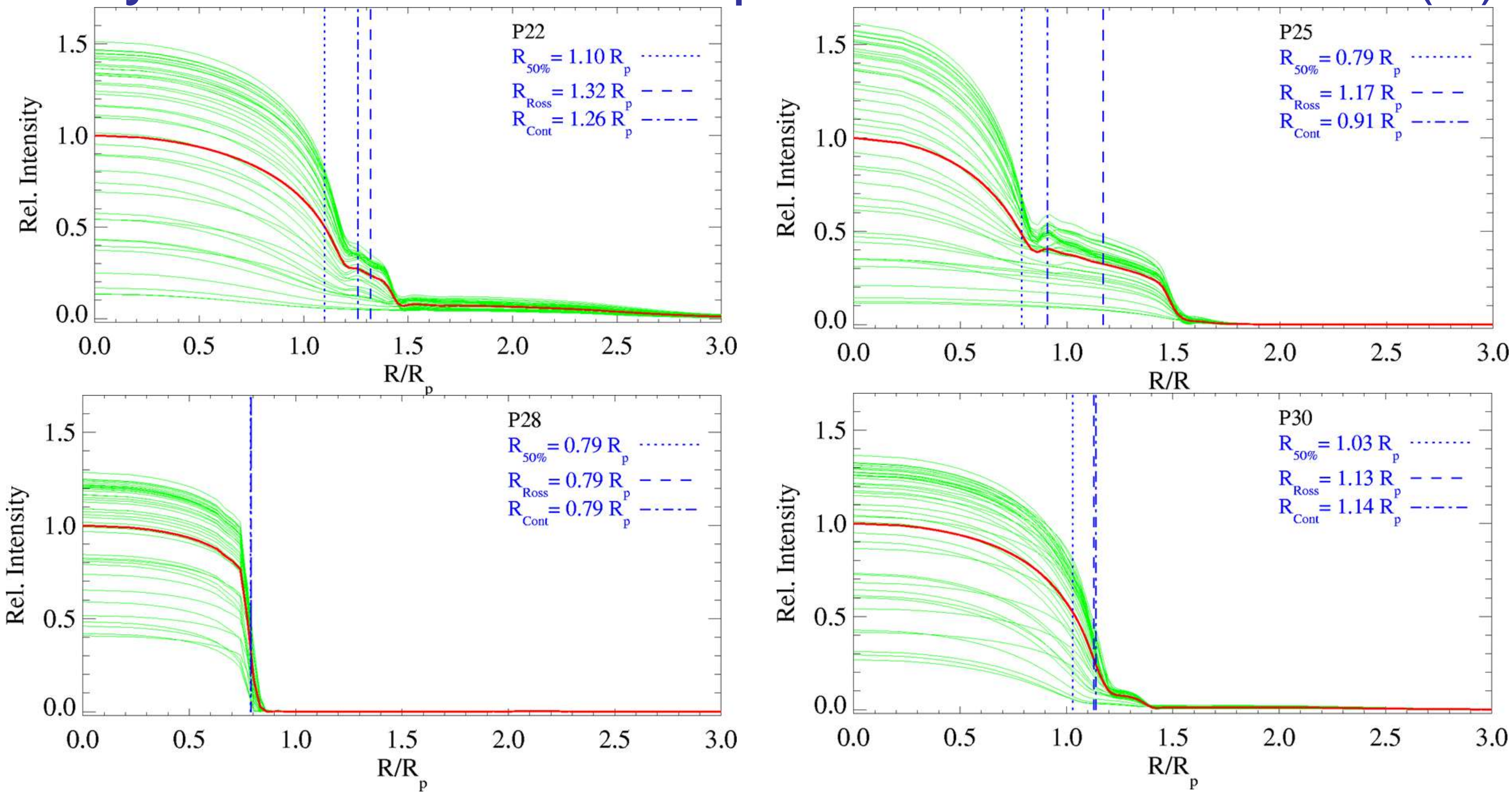
UVES

Simultaneous comparison to spectrophotometry, high-resolution echelle spectroscopy, and interferometry provides strong tests of model atmospheres.

Wittkowski, Aufdenberg, Roccatagliata, Wolff, et al., in preparation

M. Scholz & P. Wood (2004), private communication :

Dynamic model atmospheres and Mira CLVs (K)

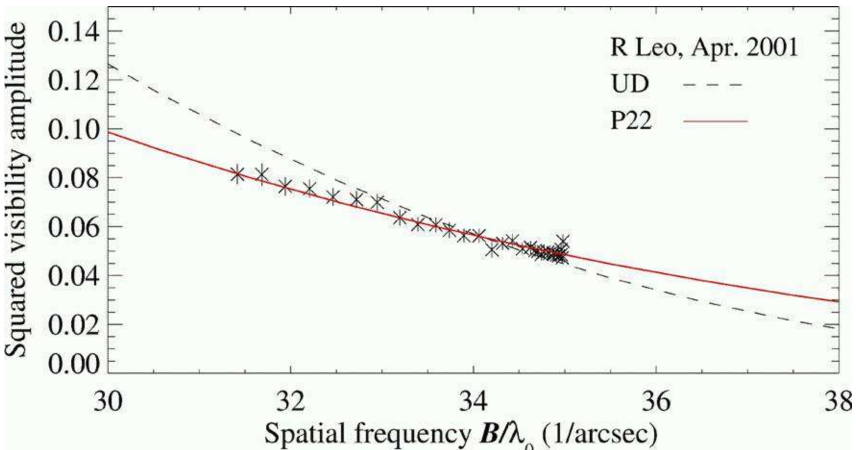


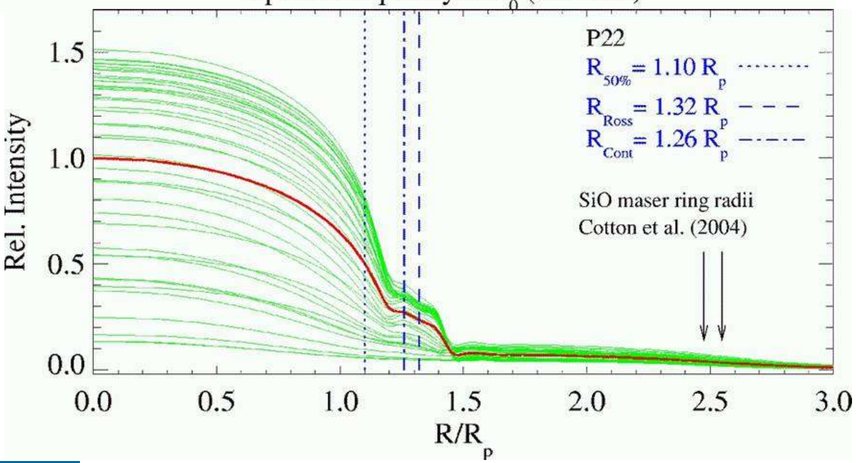
Center-to-limb variations (CLVs) are strongly affected by molecular shells.
Strong phase (and cycle) dependence.
Difficult definition of the stellar radius.

See:
Ireland et al. 2004a/b

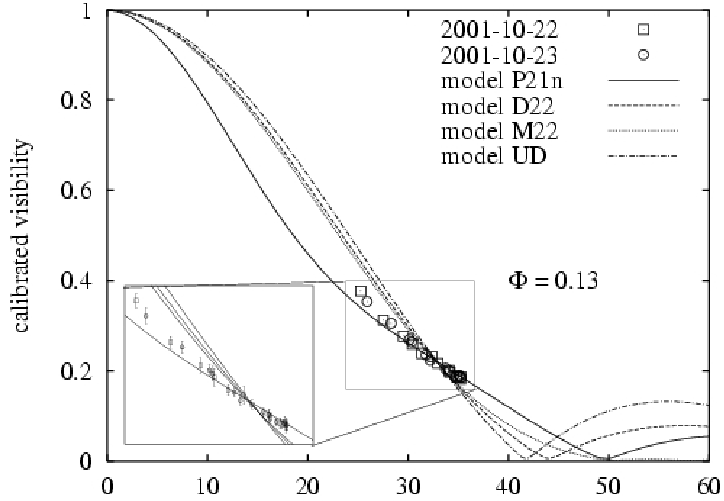
VINCI observations of the Miras o Cet and R Leo

R Leo:





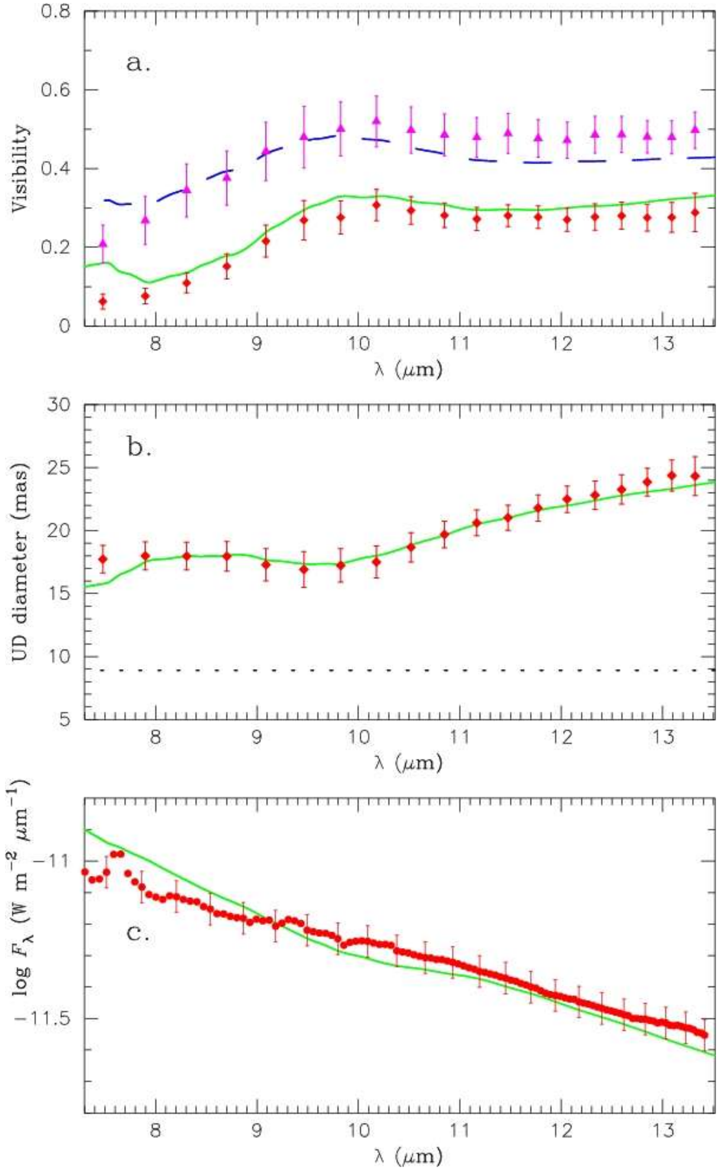
o Cet



The CLVs are different from a UD already in the first lobe, and consistent with predictions by dynamic atmosphere models that include effects by close molecular layers.

Woodruff et al. 2004
Fedele et al. 2005

MIDI observations of the Mira star RR Sco

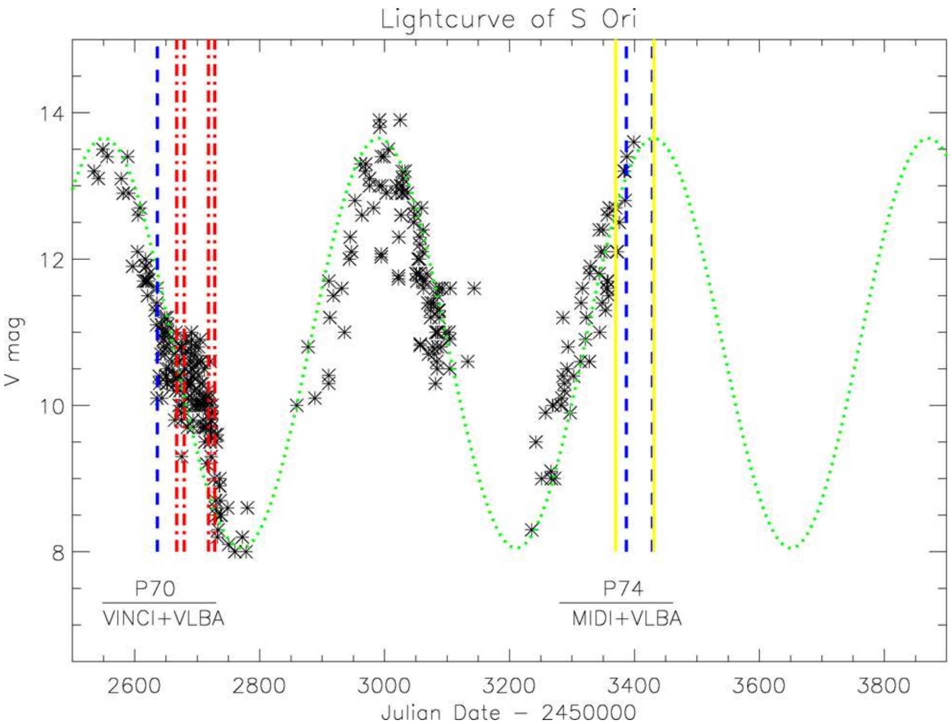


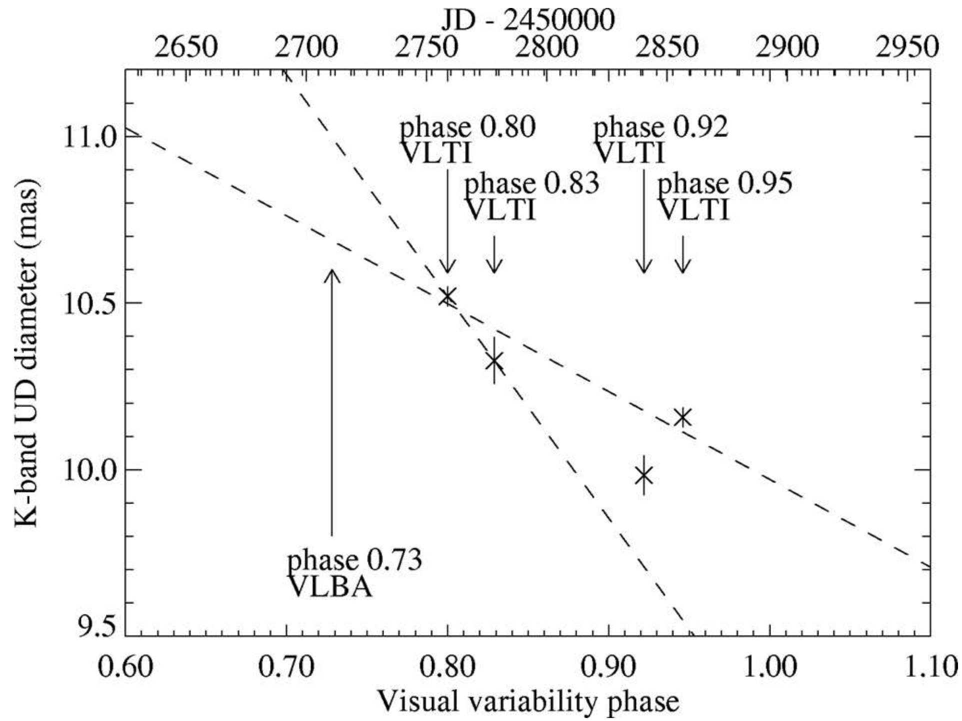
- Visibility from 7-13 microns with a spectral resolution of 30.
- Study of the molecular gas and of the dust shell.
- Equivalent uniform disk diameter increases from 15 mas @ 7 microns to 24 mas @ 13microns.
- Equivalent UD diameter in the K-band at about same time is 9 mas (VINCI).
- Molecular layer of SiO and water extending to 2.3 stellar radii with a temperature of 1400 K (opt. thick).
- Dust shell of silicate and corundum. Inner radius 7-8 stellar radii (opt. thin).

Ohnaka et al. 2005, A&A, 429, 1057

Radio, NIR, & MIR

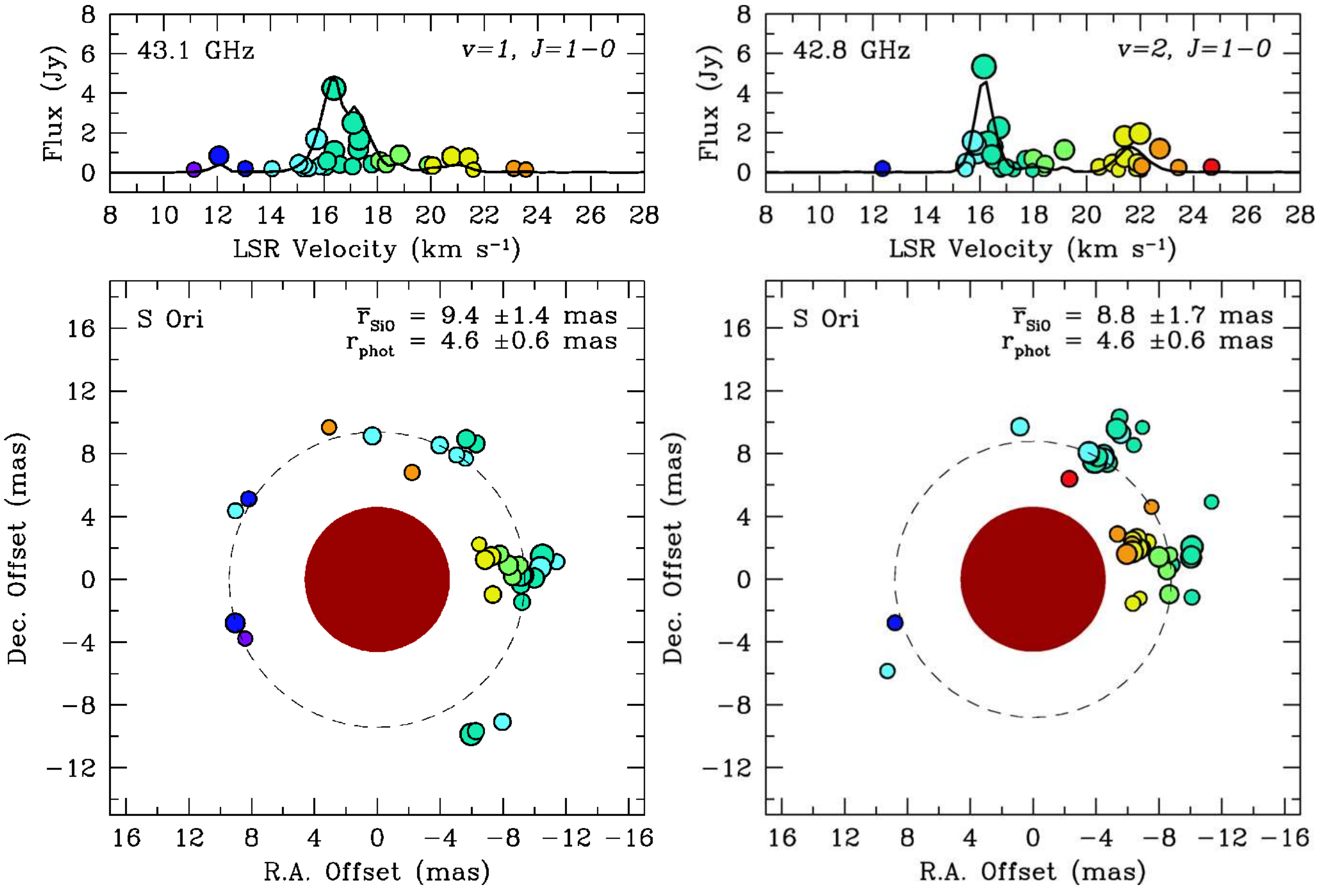
Observations of the Mira variable S Ori : Joint VLBA (SiO maser)/VLTI (VINCI) obs.; Joint VLBA (SiO maser)/VLTI (MIDI) obs.

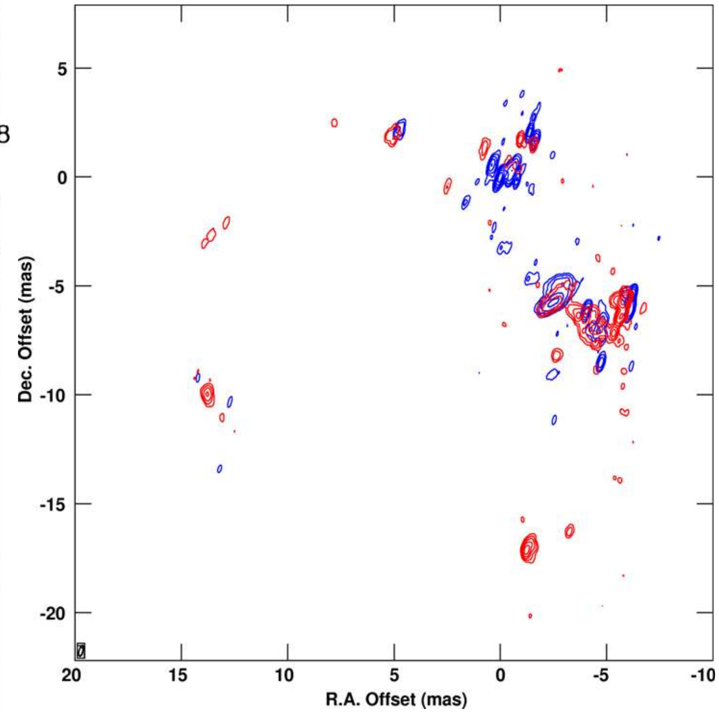




Boboltz & Wittkowski 2005, ApJ, 618, 953
Boboltz, Driebe, Ohnaka, Wittkowski, in prep.

Joint VLBA/VINCI observations of S Ori (Dec 2002)





Boboltz & Wittkowski 2005

Joint VLBA/VLTI observations of S Ori (Dec. 2002)

- First-ever coordinated observations between VLBA and VLTI.
- Simultaneous VLBA observations of the 43.1 GHz and 42.8 GHz SiO maser emission toward S Ori (phase 0.73).
- Coordinated K-band VINCI observations (phase 0.8-0.95).
- Average distance of the masers from the center of the distribution is 9.4 mas and 8.8 mas for the two transitions. No significant inidication of global infall, expansion, or rotation.
- K-band UD diameter decreases from ~10.5 mas to ~10.2 mas
- UD diameter extrapolated to 0.73 and corrected to a Rosseland / continuum diameter using model atmospheres: 9.2 mas (at pre-maximum phases: small corrrection, intensity profile relatively close to a UD).
- Average distance of the maser spots from the stellar surface: 2.0/1.9 R_*
- This result is virtually free of the usual uncertainty inherent in combining observations widely separated in time/stellar phase.

Boboltz & Wittkowski 2005

Comparison to results by Cotton et al.

Table 5: SiO ring diameter variations.

Star	Mean[1]	Mean	rms[1]	percent[1]	Mean[2]	Mean	rms[2]	percent[2]
	(mas)	(2 $R_{2.2\,\mu m}$)	(mas)	(%)	(mas)	(2 $R_{2.2\,\mu m}$)	(%)	
omicron Ceti	70.3	2.88	7.0	10	68.3	2.80	5.0	7
U Orionis	29.3	1.88	1.0	3	27.5	1.76	0.2	0.7
R Leonis	57.4	1.95	4.3	8	54.5	1.85	5.3	10
S Coronae Boralis	20.6	1.82	1.9	9	18.9	1.67	0.5	3
U Herculis	25.3	2.30	1.6	9	22.6	2.06	1.7	8
R Aquarii	32.6	1.93			31.9	1.90		
R Cassopeiae	49.9	2.01			45.9	1.85		

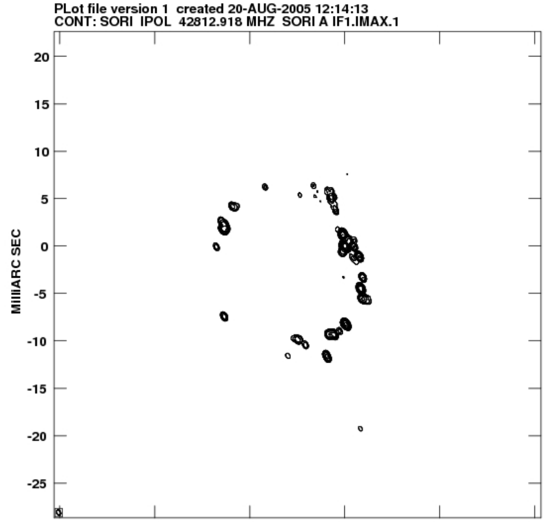
[1] $v = 1$, J=1-0 transition of SiO at 43.1 GHz.

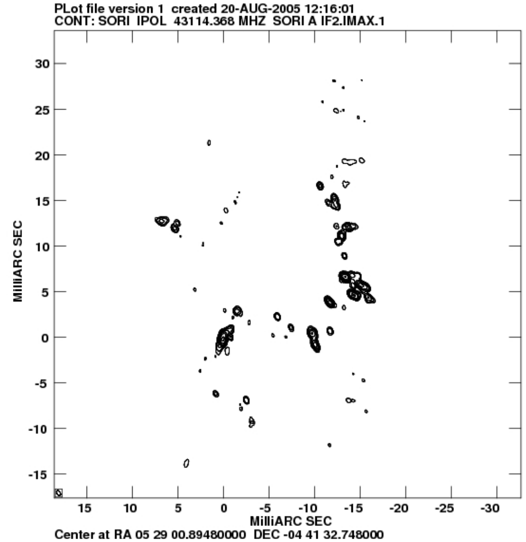
[2] $v = 2$, J=1-0 transition of SiO at 42.8 GHz.

Cotton et al. 2004: Comparison of near-infrared diameters obtained with the IOTA interferometer and SiO maser ring diameters obtained with the VLBA.

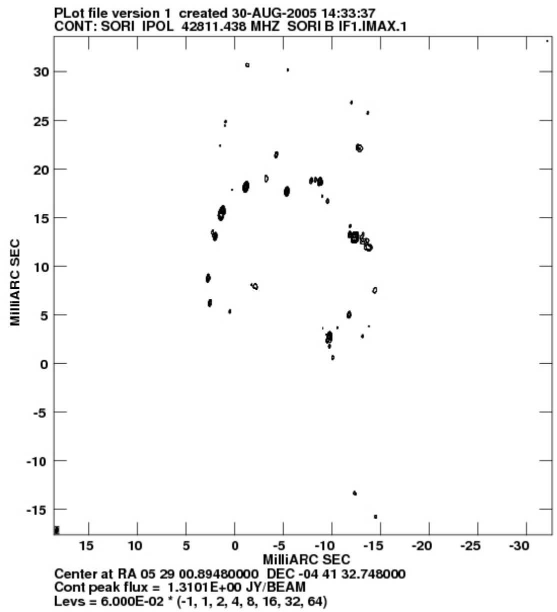
VLBA (and MIDI) observations of S Ori (2005)

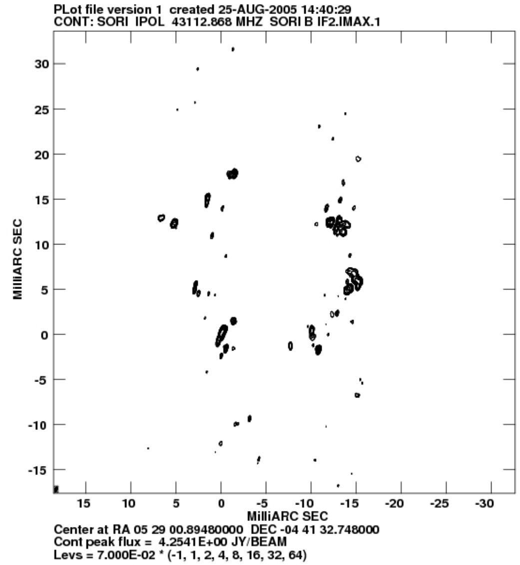
Jan 2005





Feb 2005





42.8 GHz

43.1 GHz

Joint VLTI/MIDI and VLBA/SiO observations of the Mira star RR Aql and the supergiant AH Sco

- RR Aql:

  VLTI/MIDI observations : April 2004, July 2004, April 2005

  VLBA/SiO maser observations: July 2004, August 2005

  (~3 weeks difference)

- AH Sco:

  VLTI/MIDI observations: April 2004, July 2004

  VLBA/SiO maser observations: July 2004, August 2005

Boboltz, Driebe, Ohnaka, Wittkowski, in prep.

Summary

- Interferometric observations provide fundamental stellar parameters.
- VLTI/AMBER can probe the intensity profile across the stellar disk, ultimately including surface structure (inhomogeneities).
- VLTI/AMBER & VLTI/MIDI can probe the effects by molecular shells close to continuum-forming layers.
- VLTI/MIDI can probe the parameters of circumstellar dust shells.
- VLBA can probe the morphology and kinematics of maser shells (SiO, OH, H_2O).
- Concurrent studies will improve our understanding of the structure of the CSE and the mass-loss process.
- Such concurrent and multi-wavelength studies will ultimately help to better understand the transition from circularly symmetric AGB stars to axisymmetric/bipolar PNe.
- Synergies with other facilities such as ALMA are promising as well.

Observing with the VLT Interferometer

- First Fringes: March 2001 (Siderostats).
- Shared-risk science observations in P70/71 (2002/2003).
- Science demonstration and guaranteed time observations with AMBER and MIDI.
- MIDI offered for regular service and visitor mode observations since P73 (observations since April 2004, limited modes, UTs only). For P76 (observations from October 2005) with additional modes, and also with ATs.
- AMBER offered for regular service and visitor mode observations with the UTs since P76.
- Same kind and level of user support as for any other VLT instrument.
- 66 approved and scheduled programs in P73-P75. 71 proposals submitted for P76 (AMBER & MIDI).
- Call for Proposals for P77 is released today, observations April to September 2006, deadline 30 Sep.