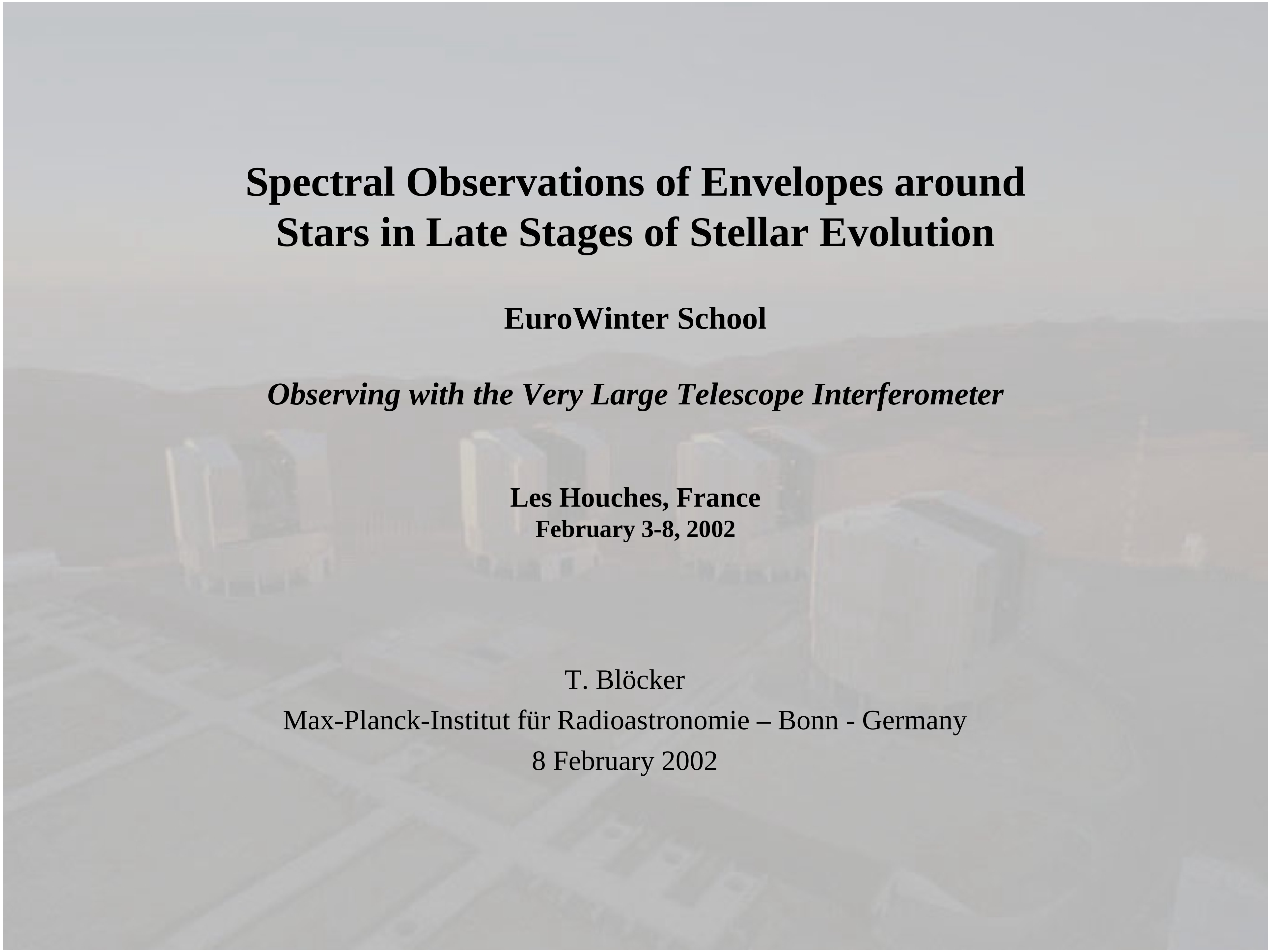


Spectral Observations of Envelopes around Stars in Late Stages of Stellar Evolution

EuroWinter School

Observing with the Very Large Telescope Interferometer

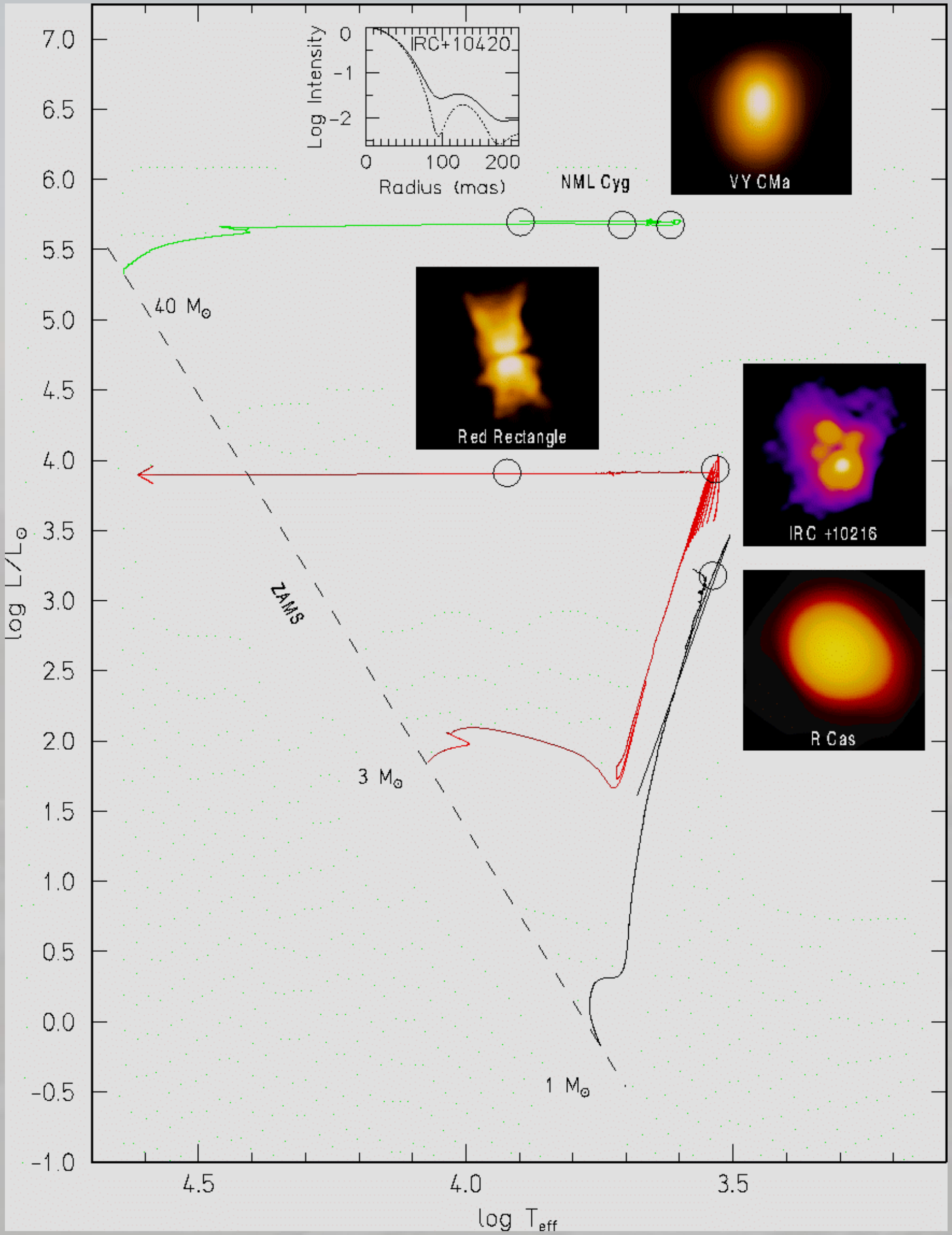
Les Houches, France
February 3-8, 2002

T. Blöcker
Max-Planck-Institut für Radioastronomie – Bonn - Germany
8 February 2002

Outline

- Stars in late stages of stellar evolution
- Dust-shells: Observations
- Radiative transfer calculations
- Long Baseline Interferometry
- Projects for the VLTI
- Conclusions

Stellar Evolution



late stages of stellar evolution:

strong stellar winds lead to obscuration by dust

absorbtion of visible light and re-emission in the infrared

Dust enshrouded objects:

Asymptotic Giant Branch (AGB)
R Cas, IRC+10216; CIT3, CIT6

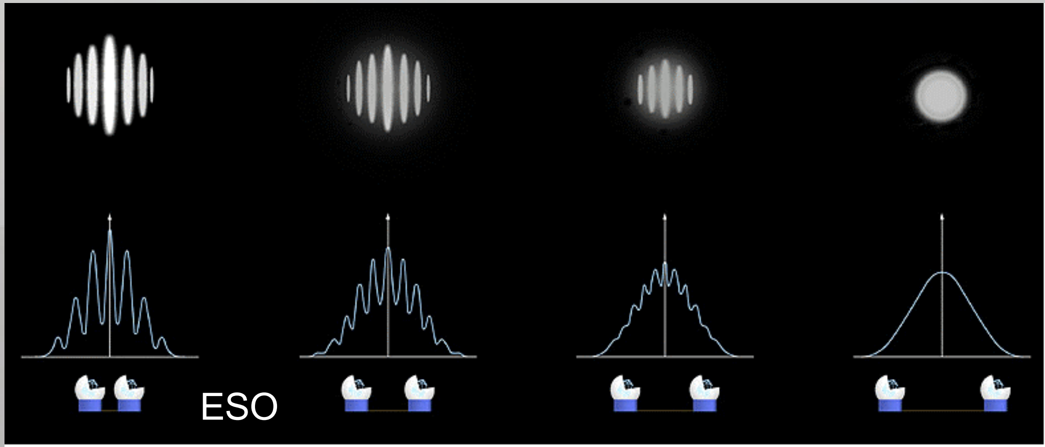
Protoplanetary Nebula Phase
Red Rectangle, Egg Nebula

Red Supergiant Branch (+ WR)
NML Cyg, IRC+10420, VY CMa

The dusty environment of evolved stars

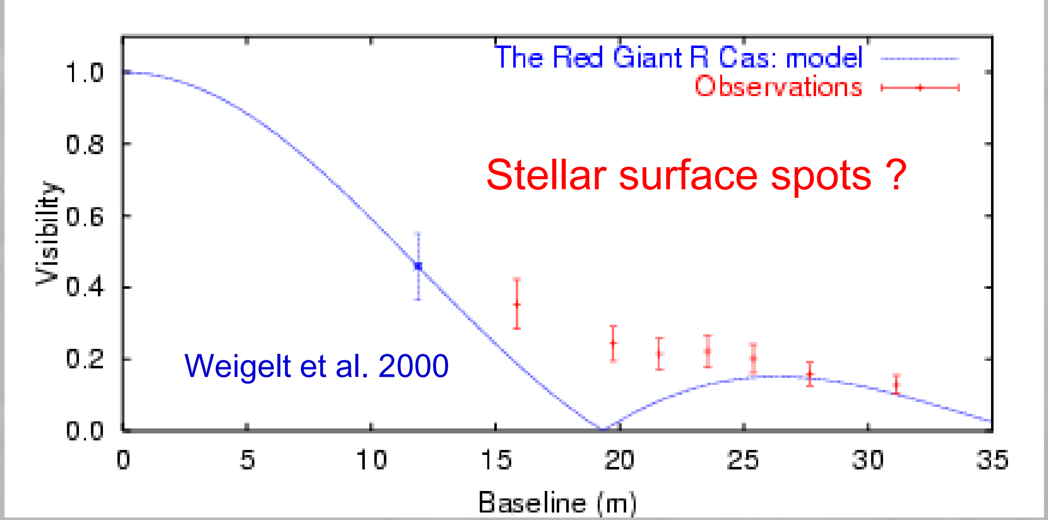
AGB stars	• main factories of cosmic dust. • strong mass loss: up to 10^{-4} $M_{\odot}$/yr • dust shells: many: spherical symmetry on large scales a few: asymmetric on subarcsecond scales • surface structures, diameters
Protoplanetary Nebulae	• axisymmetry, bipolar cavities
Massive Supergiants	• episodic mass-loss; outbursts
Wolf-Rayet stars	• dust production in hostile environment

Diameters & Surface Structures



first zero of visibility:

- ➢ stellar diameter



Stellar surface spots ?

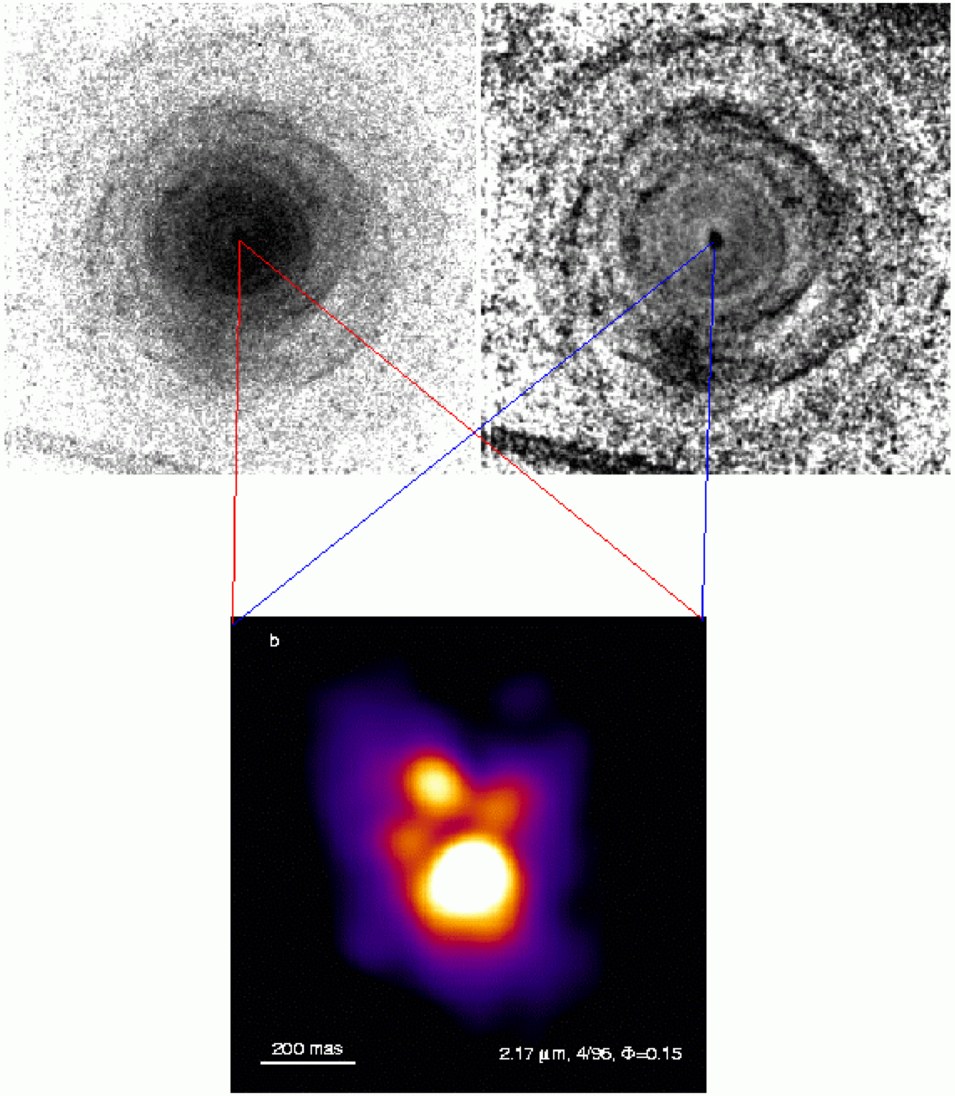
Weigelt et al. 2000

K band GI2T observations

R Leo: IOTA (Perrin et al. 1999)

The dust shell of IRC+10216

Composite $B + V$ images (131" × 131") Mauron & Huggins 1999

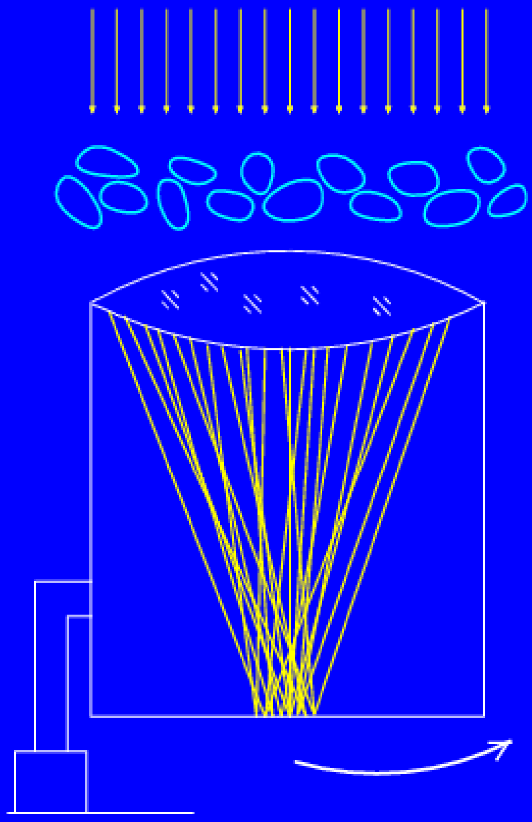


K image (1" × 1", resolution: 0.07") Weigelt et al. 1998

optical

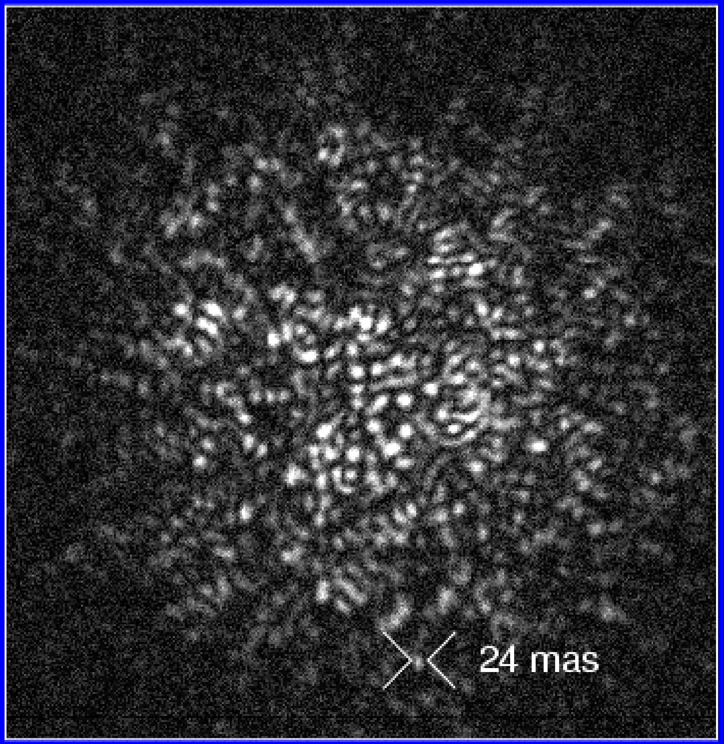
near infrared

Speckle Interferometry



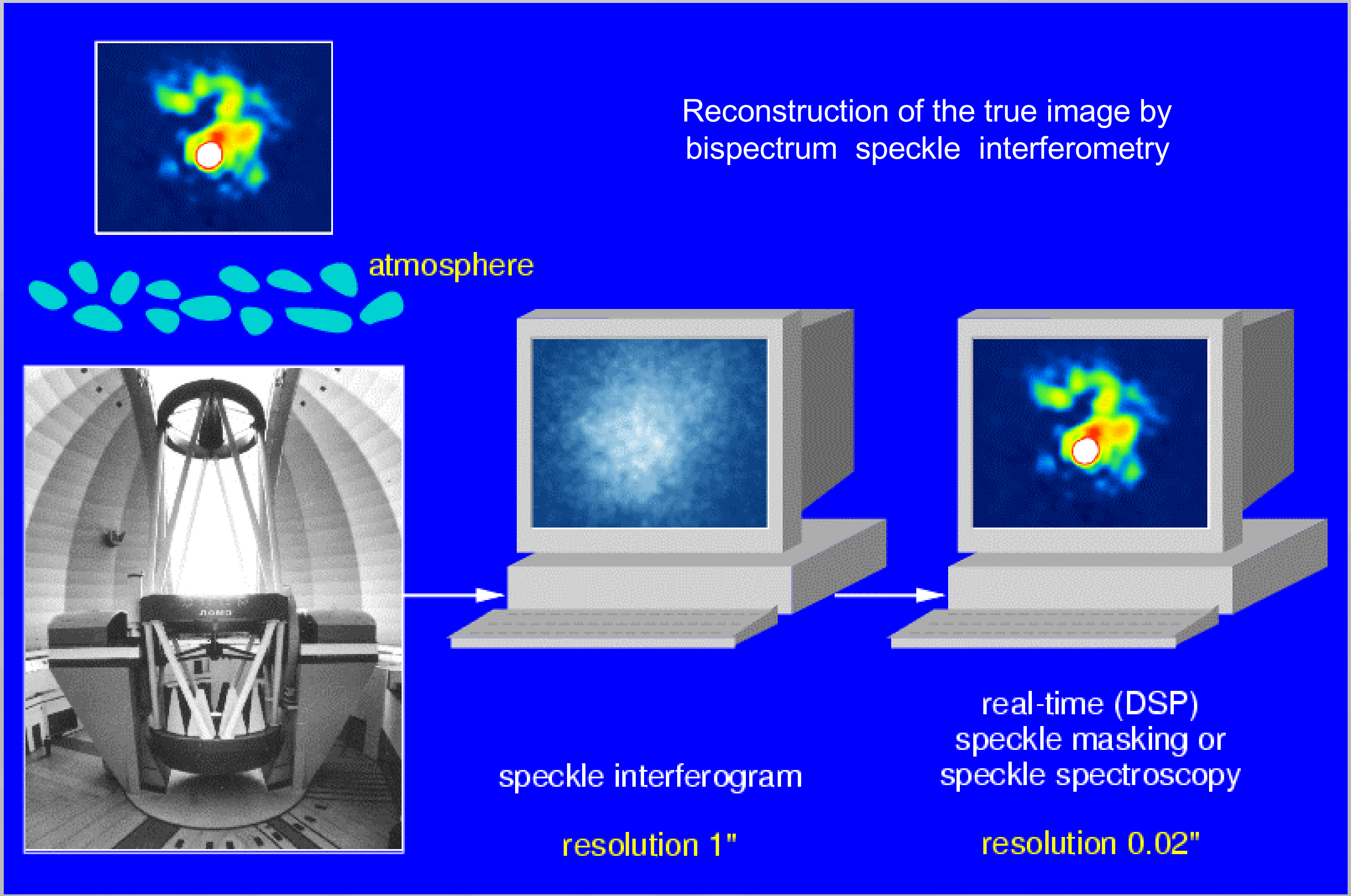
atmosphere
telescope
speckle interferogram

Short exposure (50ms) freeze the atmospheric turbulence



speckle interferogram
6 m telescope, γ Ori, $\lambda = 500$ nm
field of view 1.84 arcsec

Speckle Interferometry



Reconstruction of the true image by
bispectrum speckle interferometry

atmosphere

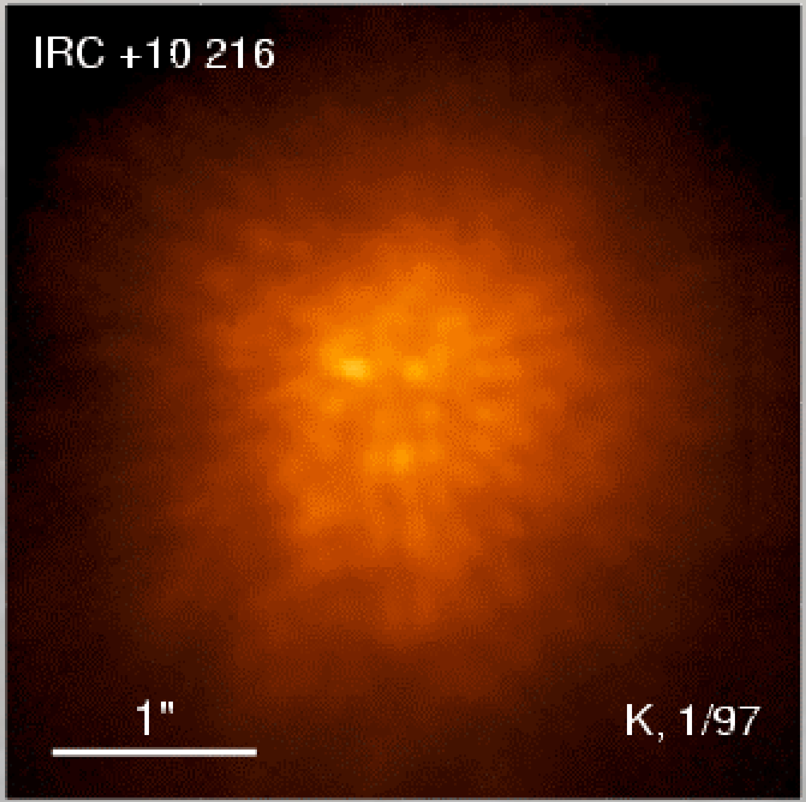
speckle interferogram

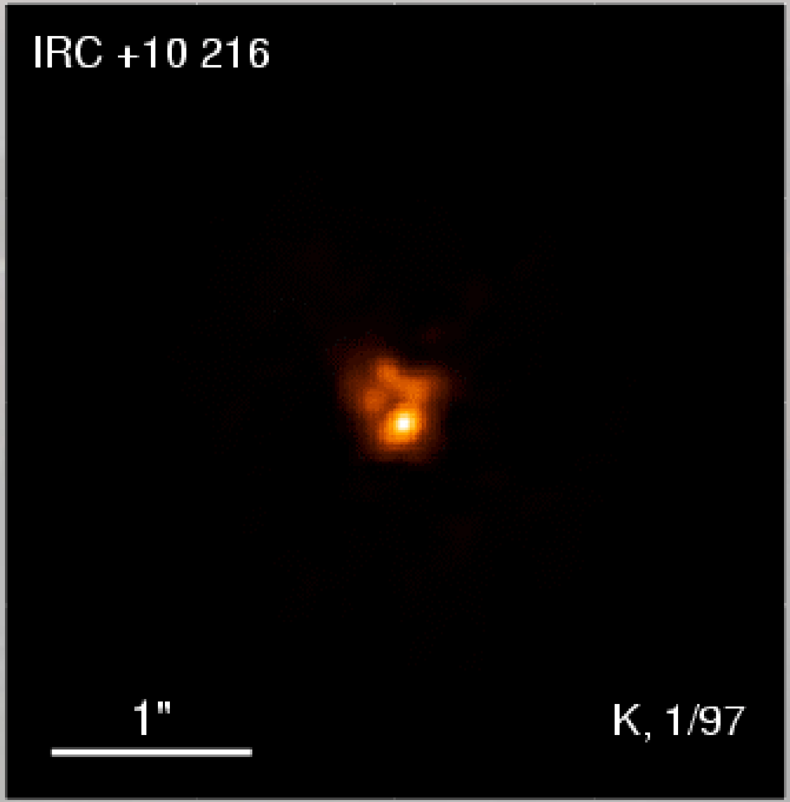
resolution 1"

real-time (DSP)
speckle masking or
speckle spectroscopy

resolution 0.02"

IRC+10216 before and after reconstruction



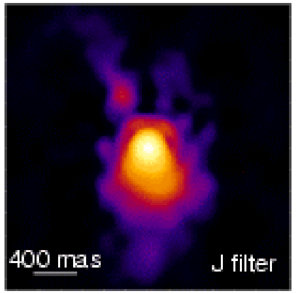


JHK images of the carbon star IRC+10216

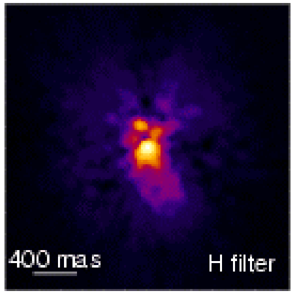
Speckle interferometry at the SAO 6m telescope

IRC +10 216: best studied carbon star and one of the brightest infrared sources

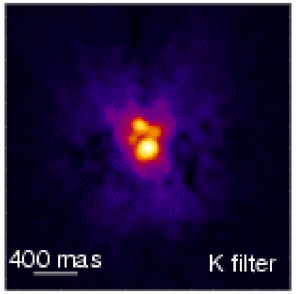
mass loss ≈ several 10^{-5}M$_\odot$/yr ; pulsational period: 649 d ; $d = 110 - 170$ pc



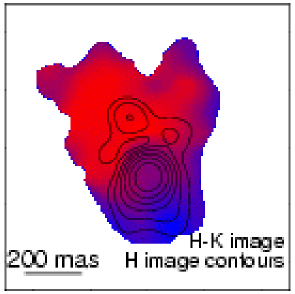
1.24 μm (J), 4/1996



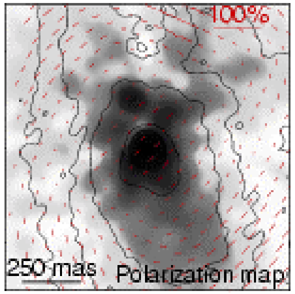
1.64 μm (H), 1/1997



2.2 μm (K), 1/1997



H-K color image



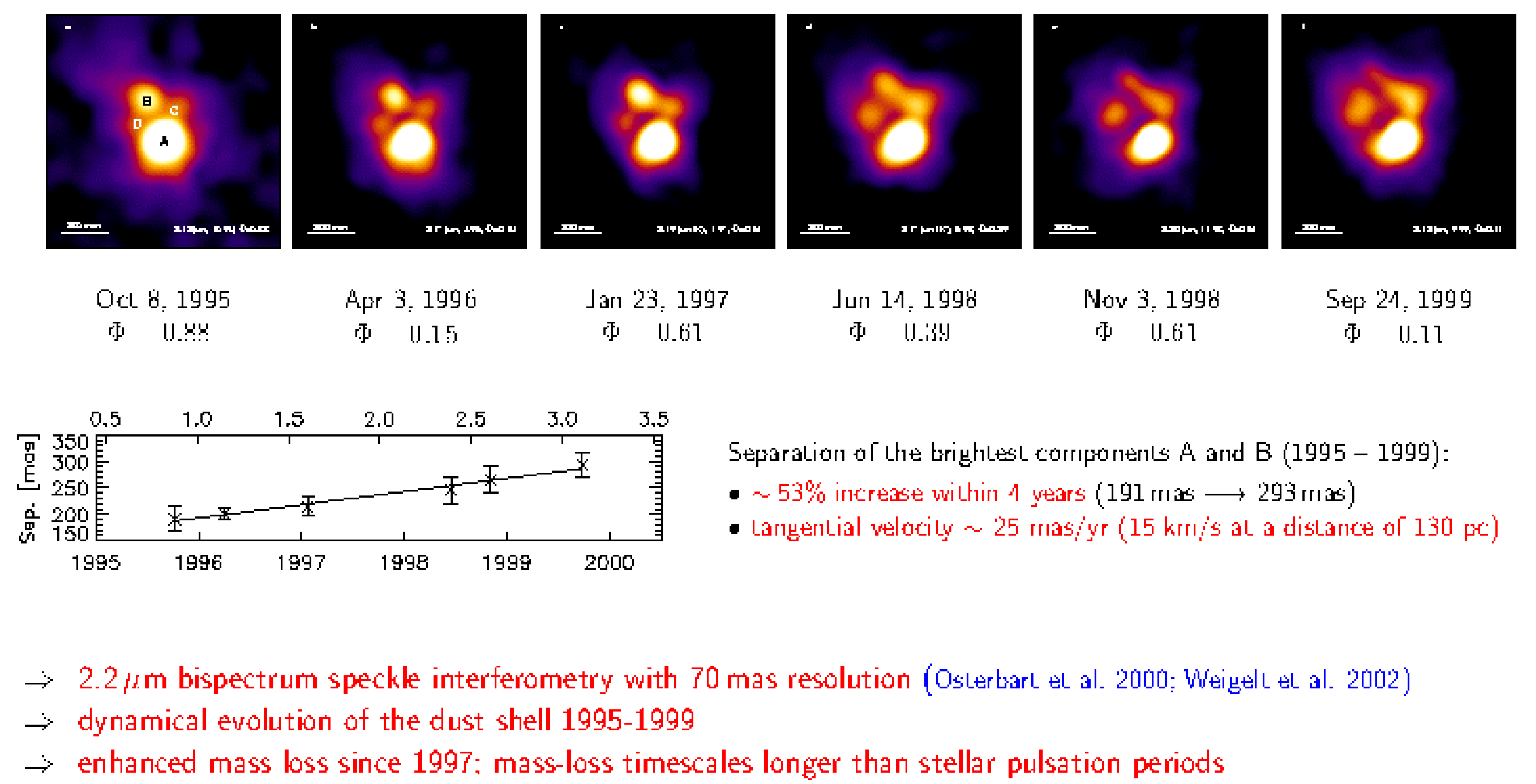
1.1 μm HST data

- IRC +10 216 consists of a number of resolved, bright components within a ~200 mas radius and a fainter bipolar nebula.
- The center of the centro-symmetric polarization pattern does not coincide with the brightest component but is located north.

⇒ very advanced stage of AGB evolution; possibly in a phase immediately before moving off the AGB or even in the early stages of transformation into a protoplanetary nebula

⇒ central star close to northern (second brightest) component between southern and northern J-band lobes consistent with 2-dimensional radiative transfer (Menshchikov et al. 2001)

Dust shell evolution of IRC+10216 in the K band



Oct 8, 1995	Apr 3, 1996	Jan 23, 1997	Jun 14, 1998	Nov 3, 1998	Sep 24, 1999
Φ 0.88	Φ 0.15	Φ 0.61	Φ 0.39	Φ 0.61	Φ 0.11

Separation of the brightest components A and B (1995 – 1999):

- ~ 53% increase within 4 years (191 mas ⟶ 293 mas)
- tangential velocity ~ 25 mas/yr (15 km/s at a distance of 130 pc)

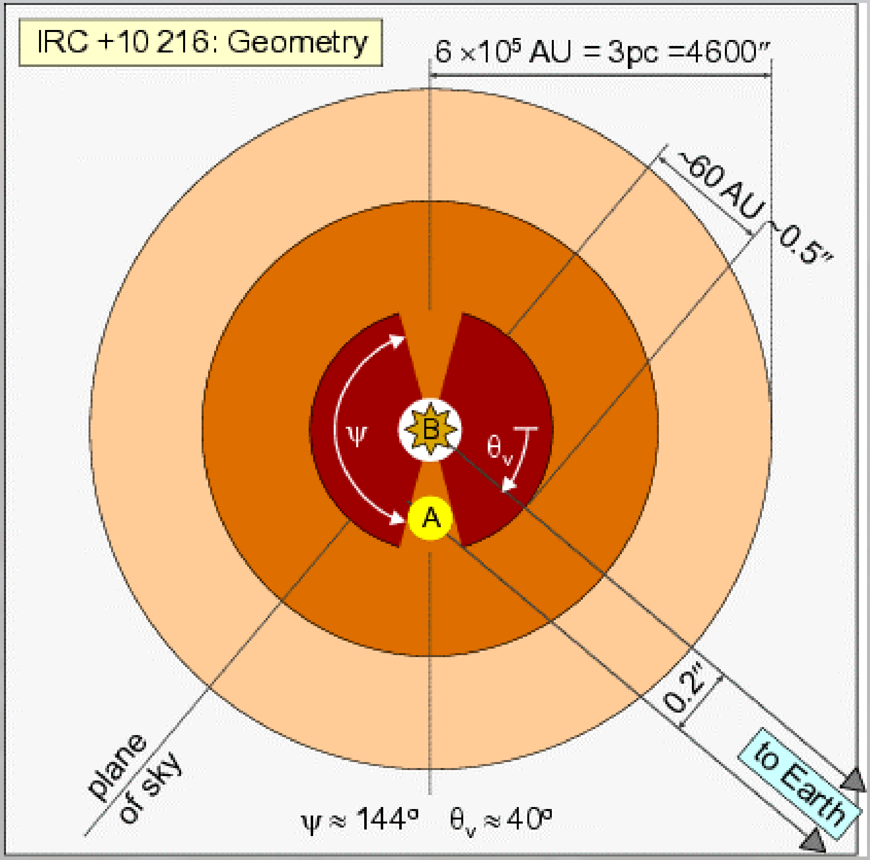
→ 2.2 μm bispectrum speckle interferometry with 70 mas resolution (Osterbart et al. 2000; Weigelt et al. 2002)

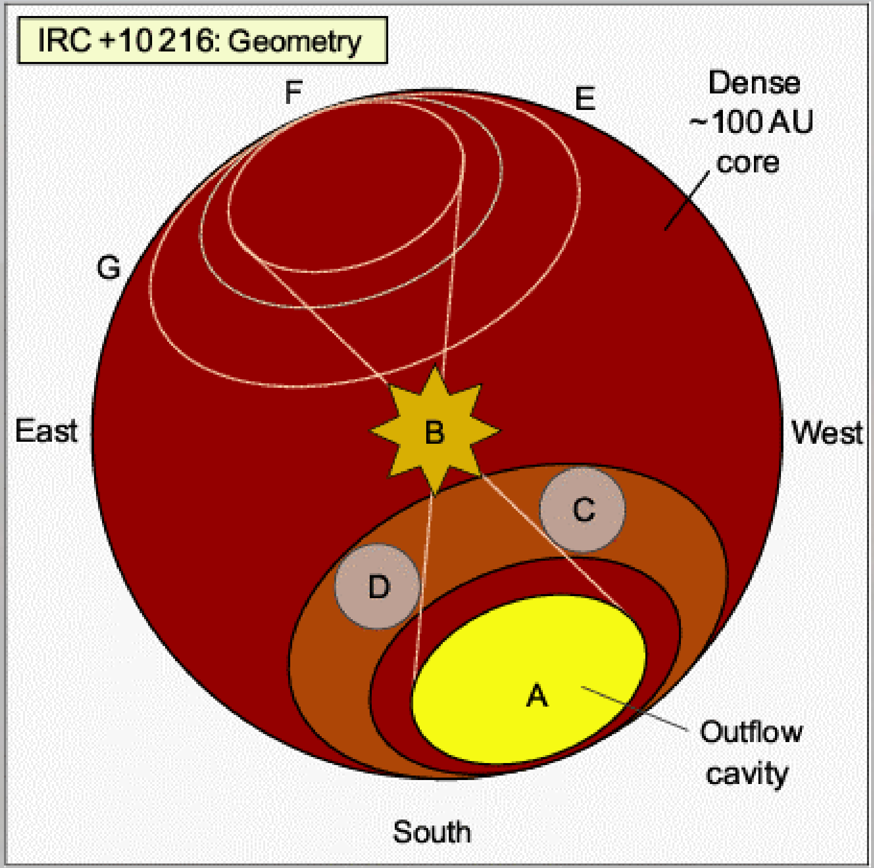
→ dynamical evolution of the dust shell 1995-1999

→ enhanced mass loss since 1997; mass-loss timescales longer than stellar pulsation periods

(see also Weigelt et al. 1998, Haniff & Buscher 1998, Tuthill et al. 2000)

2d-radiative transfer model of IRC+10216





Men’shchikov et al. (2001)

Radiative Transfer Models

- Source of radiation: black body / model atmospheres
- Effective temperature (+ gravity)
- Dust properties: optical constants (depend on chemistry, shape, etc)
- Grain size distribution
- Temperature at inner dust-shell boundary
- Density distribution
- Relative thickness of the shell (ratio of outer to inner radius)
- Optical depth at reference wavelength

- geometry: spherical symmetry / 2d / 3d
- dust formation: instantaneous / chemical network
- hydrodynamics: static / time-dependent

e.g. 1d: DUSTY (Ivezic et al. 1997); 2d: Menshchikov et al. (1997)

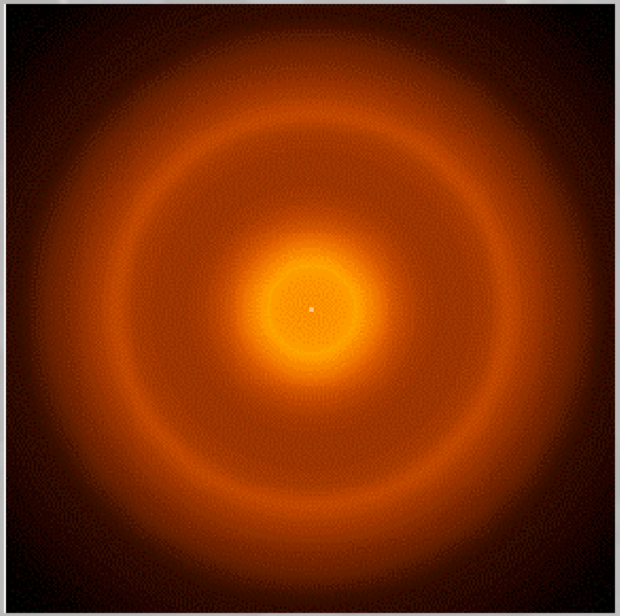
The rapidly evolving hypergiant IRC+10420

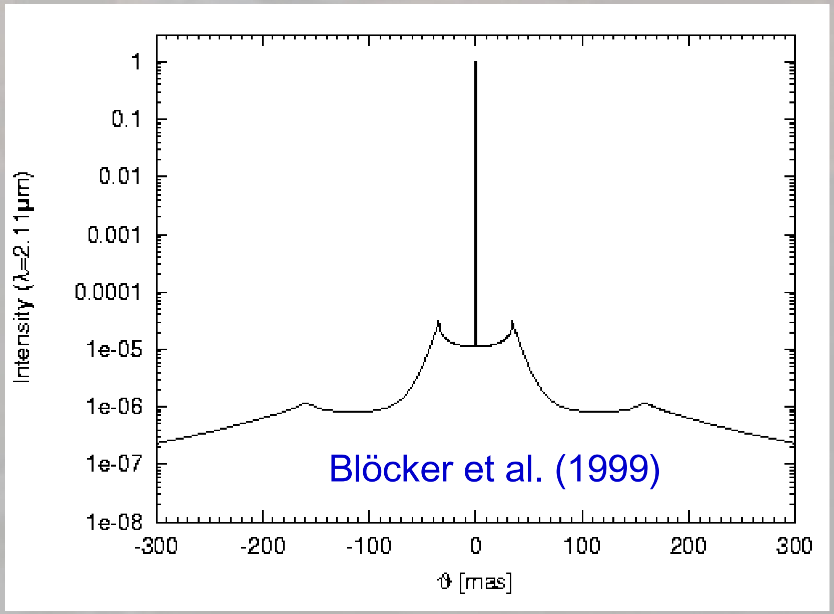
IRC+10420: *only* object currently observed in transition to Wolf-Rayet phase

Spectral type: F8 in 1973 → mid-A today : 2000 K in 30 yr !

Humphreys et al. (1973); Oudmaijer et al. (1996)

Radiative transfer modelling: 2-component shell due to previous superwind





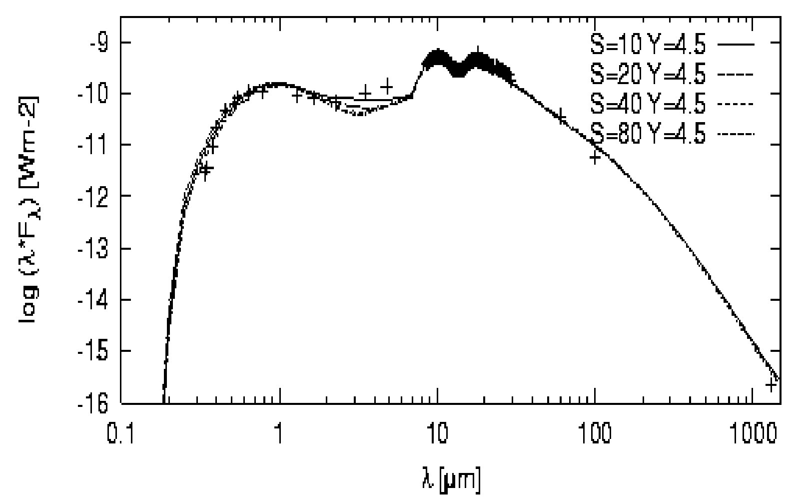
Blöcker et al. (1999)

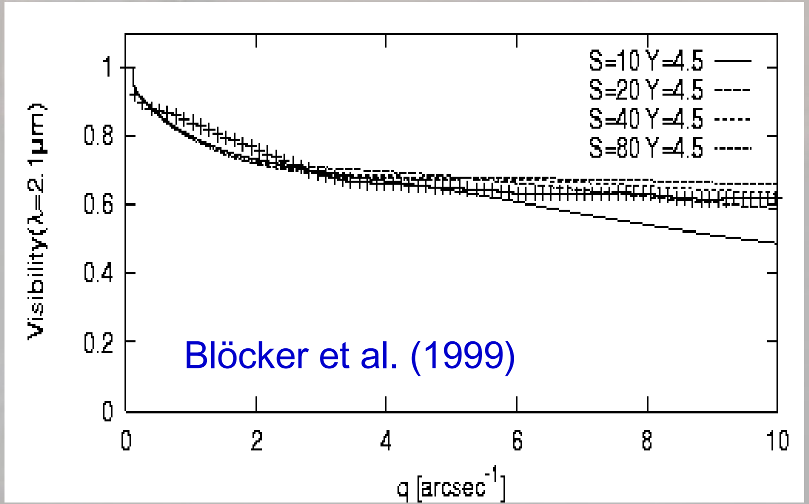
IRC+10420: SED & K-BandVisibility

Best model (Teff=7000K; silicate grains, optical depth=7)

- S=40 Y=4.5
- Inner dust shell radius: 35 mas   superwind region starts at r=135 mas

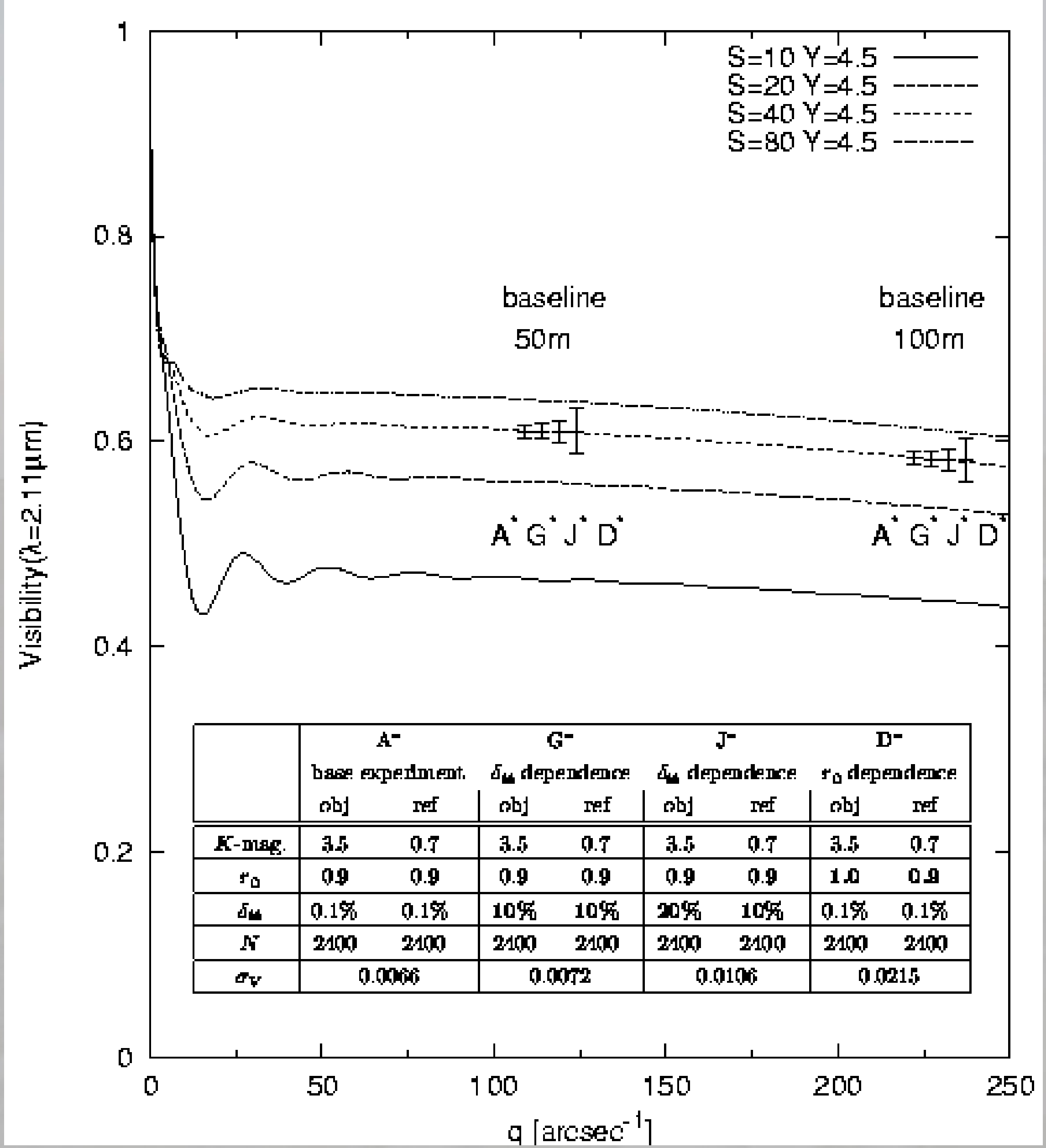
S: superwind amplitude (=density enhancement) at $Y=r/r_1$





Blöcker et al. (1999)

IRC+10420: VLTI Simulations



	A*		G*		J*		D*	
	base experiment		δ_{ss} dependence		δ_{ss} dependence		r_0 dependence	
	obj	ref	obj	ref	obj	ref	obj	ref
K-mag.	3.5	0.7	3.5	0.7	3.5	0.7	3.5	0.7
r_0	0.9	0.9	0.9	0.9	0.9	0.9	1.0	0.9
δ_{ss}	0.1%	0.1%	10%	10%	20%	10%	0.1%	0.1%
N	2100	2100	2100	2100	2100	2100	2100	2100
σ_V	0.0066		0.0072		0.0106		0.0215	

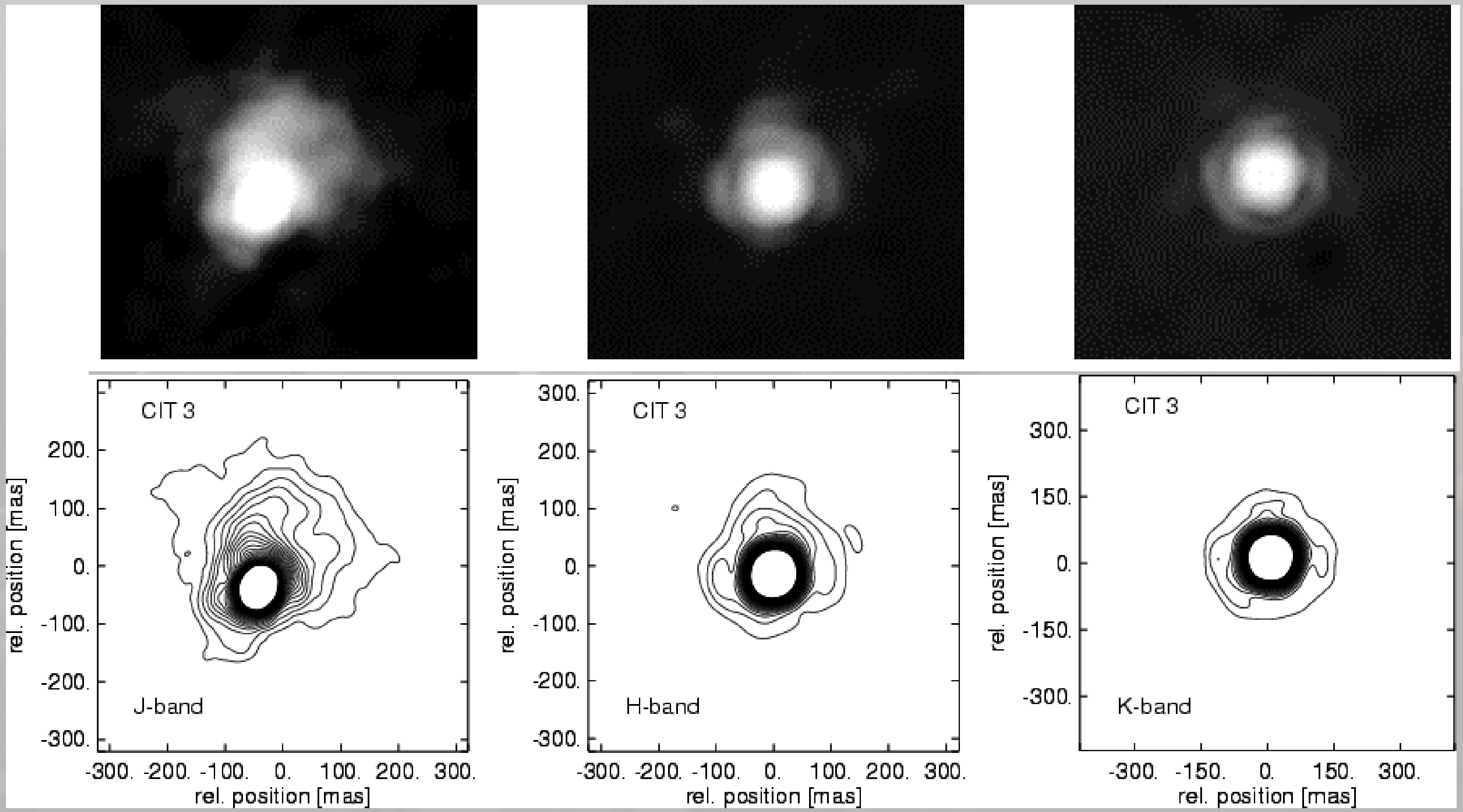
Double shell nature well constrained by observations

But: superwind strength ?

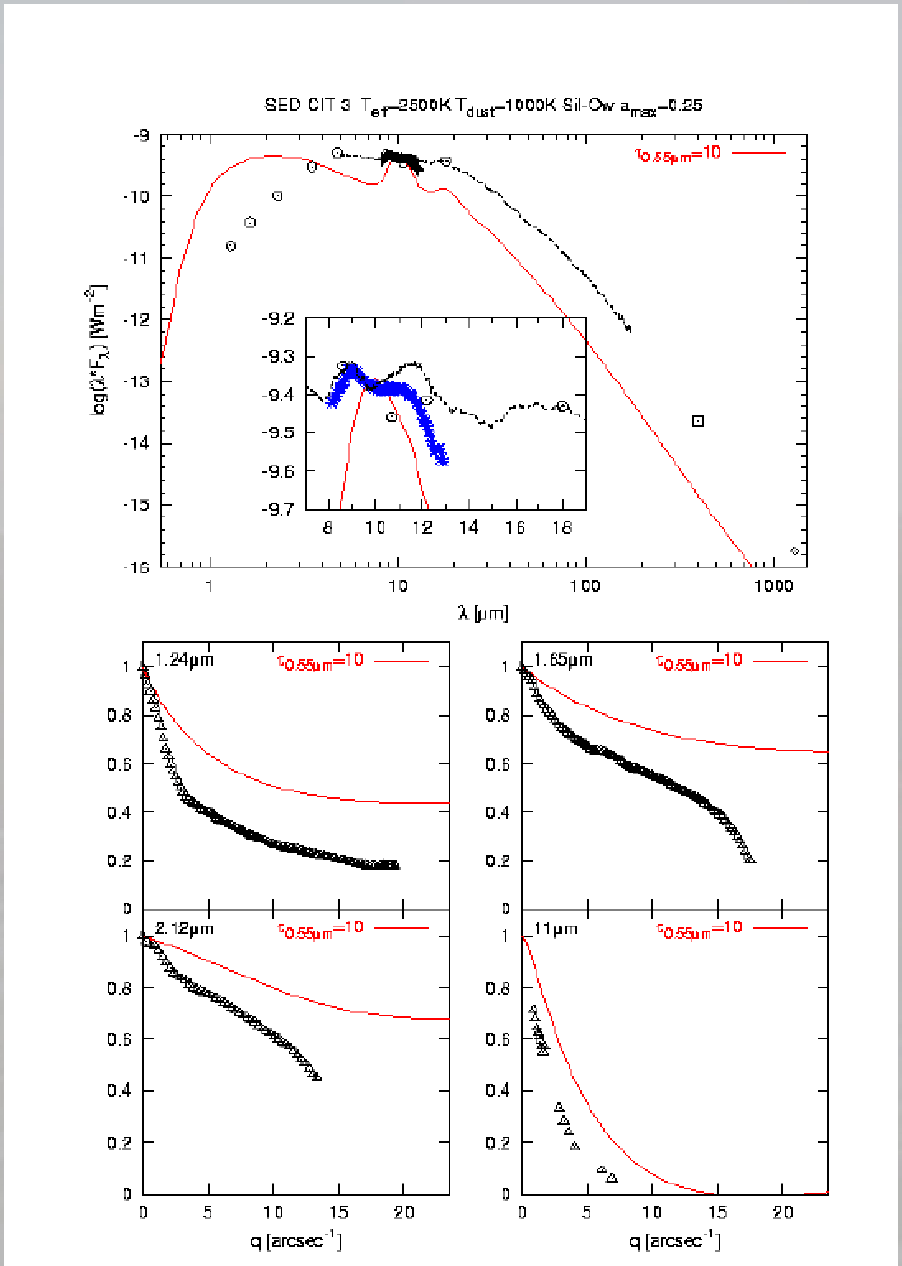
- ➢ VLTI observations will challenge existing models

Przygodda et al. 2001

The oxygen-rich AGB star CIT3



Hofmann et al. (2001)



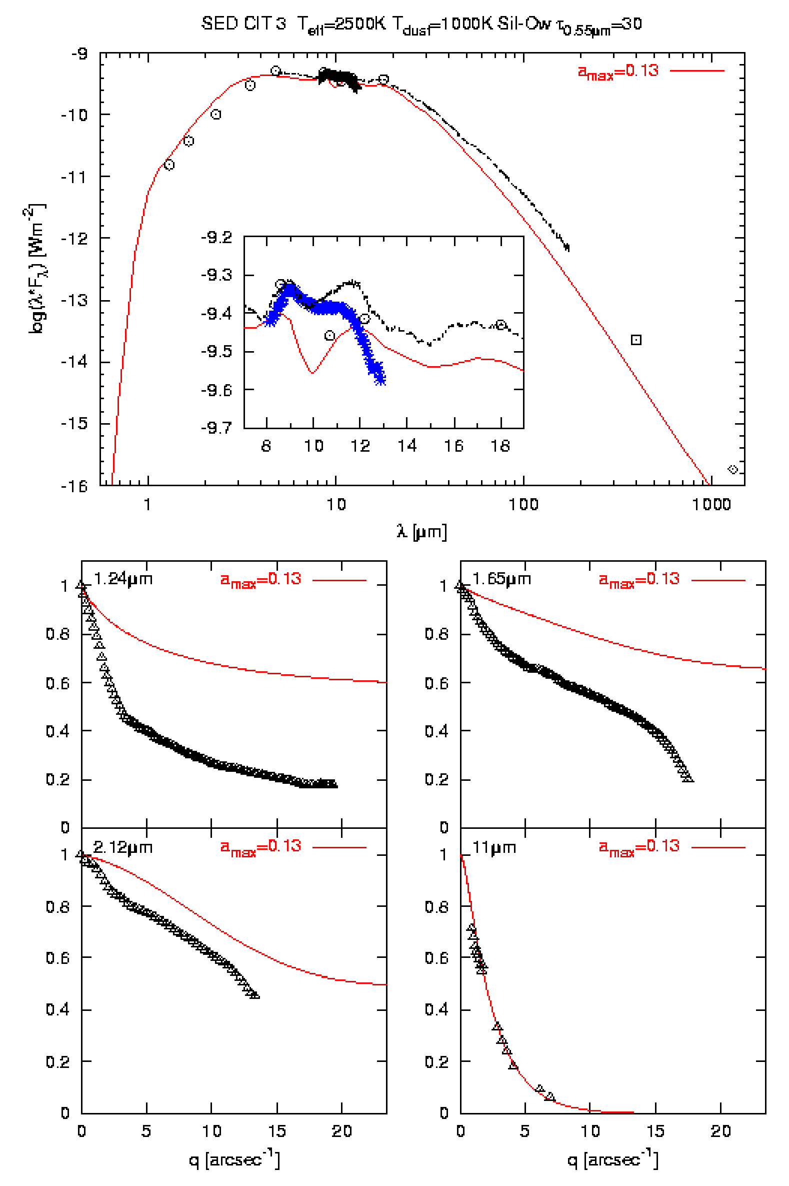
Optical depth

Optical depth at 0.55 μm:

10 to 90

JHK: 6m telescope speckle data
11 μm: ISI interferometer 4m-16m
(Lipman et al. 2000)

Size of the dust particles



$$n(a) \sim a^{-3.5}$$

$$a_{min} < a < a_{max}$$

with

$$a_{min} = 0.005\ \mu m$$

$$a_{max} = 0.13 \dots 0.45\ \mu m$$

JHK: 6m telescope speckle data
11 µm: ISI interferometer 4m-16m
(Lipman et al. 2000)

VLTI/AMBER

AMBER: Near-infrared interferometric beam combiner

- JHK
- 3 beams
- ATs: 200m baseline ~ 2mas (K)
  UTs: 130m baseline ~ 3mas (K)
- FOV (AT/UT): 250 mas / 60 mas
- R = 35, 1000, 10000

➢ Surface structures, dust shells, dust formation, atmospheres, etc…..

VLTI/AMBER

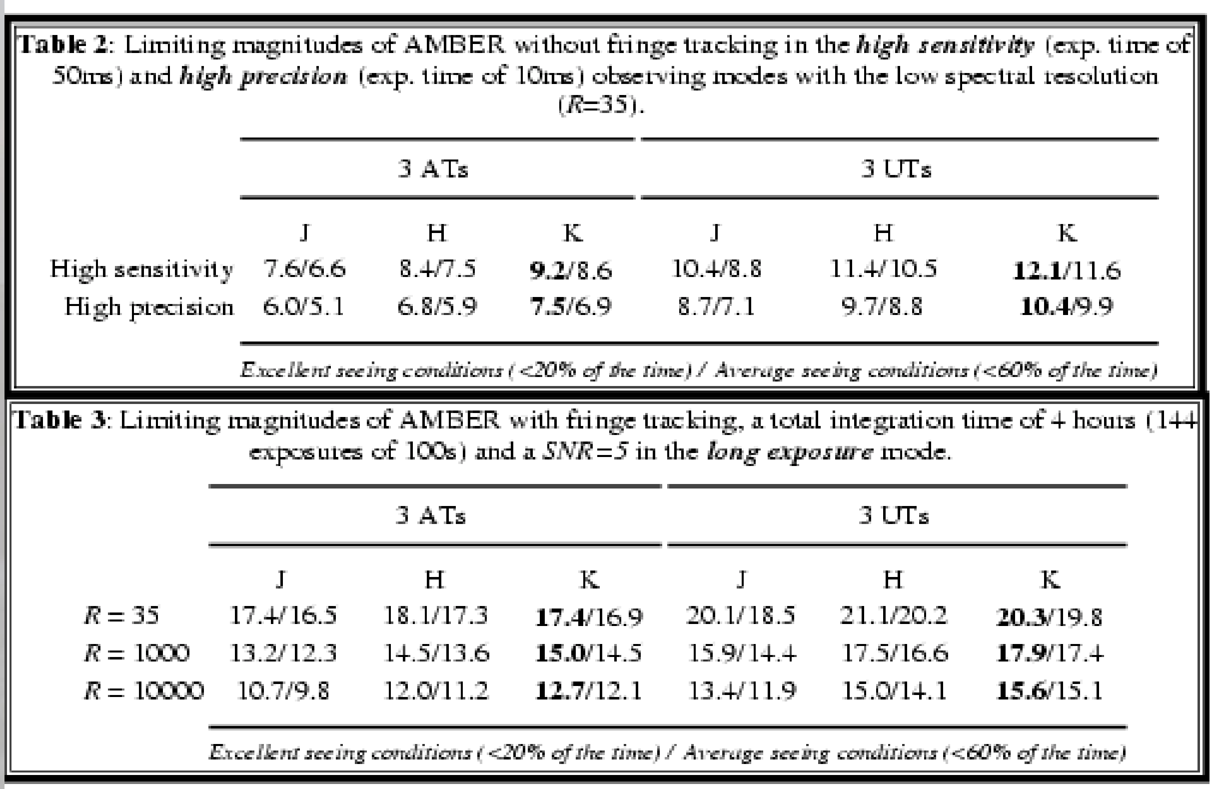


Table 2: Limiting magnitudes of AMBER without fringe tracking in the ***high sensitivity*** (exp. time of 50ms) and ***high precision*** (exp. time of 10ms) observing modes with the low spectral resolution (R=35).

	3 ATs			3 UTs		
	J	H	K	J	H	K
High sensitivity	7.6/6.6	8.4/7.5	**9.2**/8.6	10.4/8.8	11.4/10.5	**12.1**/11.6
High precision	6.0/5.1	6.8/5.9	**7.5**/6.9	8.7/7.1	9.7/8.8	**10.4**/9.9

Excellent seeing conditions (<20% of the time) / Average seeing conditions (<60% of the time)

Table 3: Limiting magnitudes of AMBER with fringe tracking, a total integration time of 4 hours (144 exposures of 100s) and a $SNR=5$ in the ***long exposure*** mode.

	3 ATs			3 UTs		
	J	H	K	J	H	K
$R = 35$	17.4/16.5	18.1/17.3	**17.4**/16.9	20.1/18.5	21.1/20.2	**20.3**/19.8
$R = 1000$	13.2/12.3	14.5/13.6	**15.0**/14.5	15.9/14.4	17.5/16.6	**17.9**/17.4
$R = 10000$	10.7/9.8	12.0/11.2	**12.7**/12.1	13.4/11.9	15.0/14.1	**15.6**/15.1

Excellent seeing conditions (<20% of the time) / Average seeing conditions (<60% of the time)

Limiting magnitudes (AT)

K = 9.2 (no fringe tracker)

17.4 (with fringe tracker)

UTs: + ~3mag

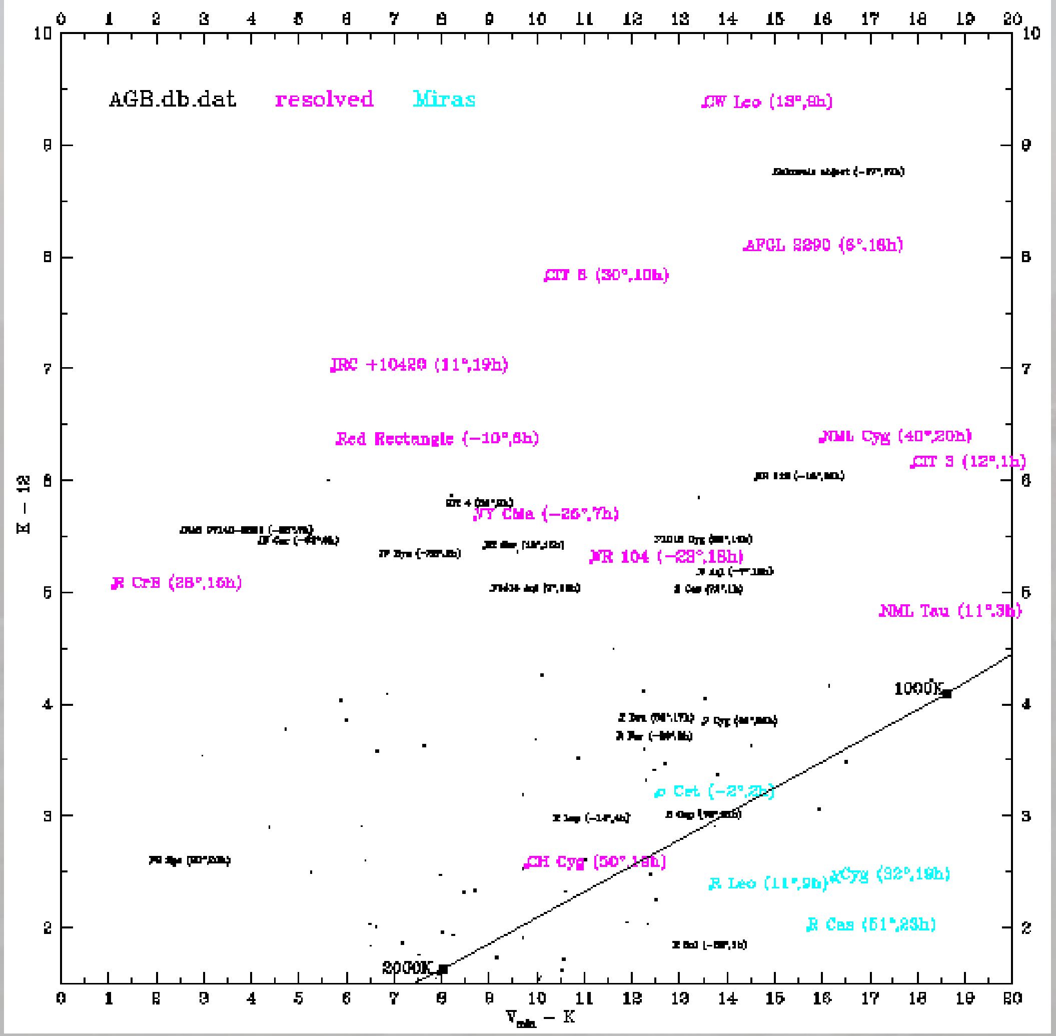
FOV: 250 mas (AT)

R. Petrov / F. Malbet

Evolved (dusty) stars: bright in K --- fainter in V --- some: extended nebulae

- Selection criteria: V-K; K-[12], K, V, FOV, ……

Looking for candidates in the two-colour diagram



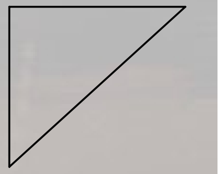
most objects resolved by speckle interferometry with 6m telescope:

K-[12] > 5

Evolved Stars & VLTI/AMBER

Example: Survey of dust shells around AGB stars

- select objects from two-colour diagram; resolved objects
- 3 ATs with short to intermediate baselines of equal length perpendicular aligned (e.g. 16m/16m/24m – 32m/32m/48m)
- JHK-LR: accuracy 1%, 3 bands crucial for models
- Single telescope data (small baselines) extremely helpful for astrophysical interpretation; new data prove models
- Chosen alignment traces deviations from spherical symmetry



➢ Study details of dust-shell structure (evolution) → mass loss

Conclusions

- VLTI observations will certainly have a large impact on the study of stars in late stages of stellar evolution (and on other objects (YSOs,etc) as well) revealing, e.g., details of dust-shell structures and the mass-loss process.

- Radiative transfer calculations provide dust-shell properties.

  Ambiguity is largely decreased if spectral information is taken into account, i.e. photometry/spectroscopy and visibilities at various wavelenghts probing, e.g., scattering (J), hot dust (H,K), or cool dust (N).

- Combination of long-baseline interferometry data with high-resolution data at short baselines (speckle, AO) will be very helpful for interpretation.