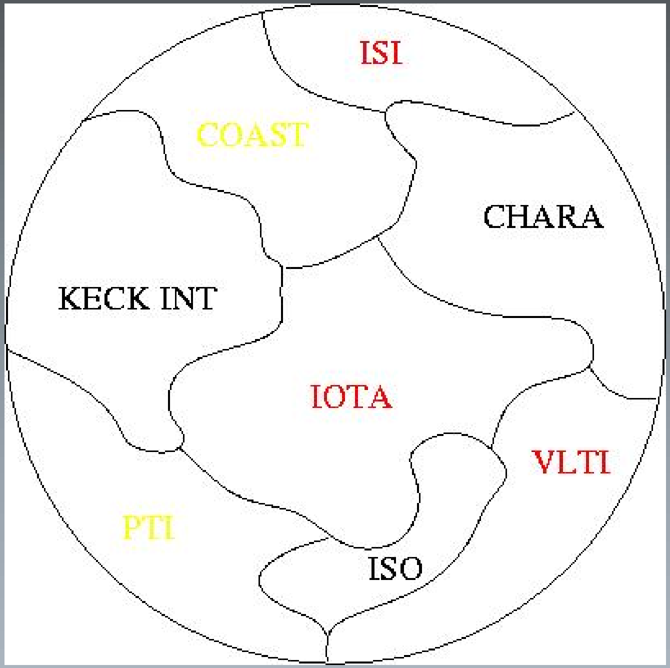
Studying Evolved Stars: What can be learnt from optical/infrared interferometry?



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Michelson Summer School
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“Evolved Stars”

- Red giants and supergiants in the He burning phase

  or in a later stage of stellar evolution

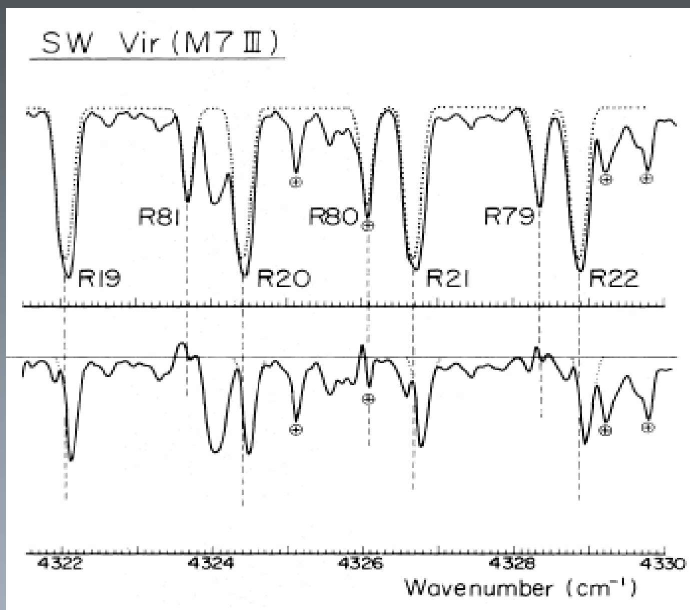
- Emphasis here on Miras and semi-regular variables

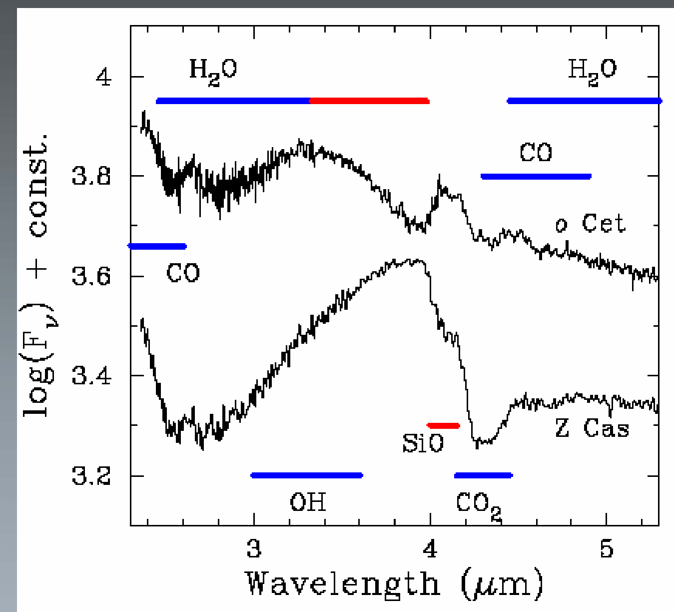
Summary

- Why long baseline stellar interferometry?
- The special case of Miras and SR variables
- Reconciling apparent mismatches: the role and impact of the molecular layer
- Applicability to variable red supergiants
- Dust chemical and spatial characterization
- Modeling difficulties – the issue of asymmetries
- Future developments and needs

Why long baseline interferometry?

- Spectroscopic measurements very useful, but interpretation quite model dependent – no direct information on the spatial scales involved



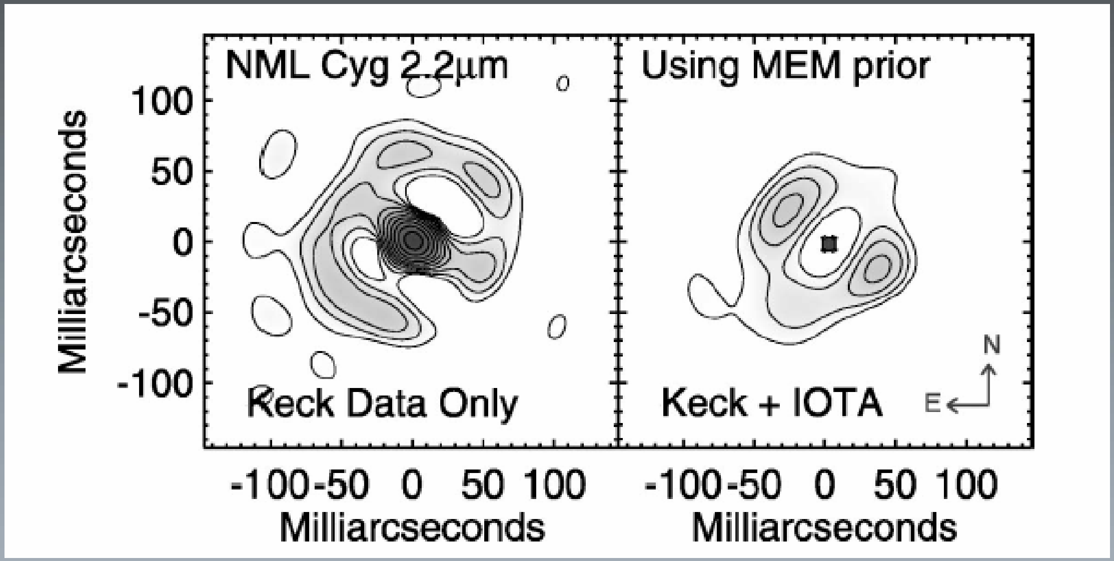


High resolution FTS spectra showing low excitation CO lines from 1670K layer distinct from the classical photosphere (Tsuji 1988, A&A 197, 185)

ISO SWS spectra (Yamamura et al. 1999, A&A 348 L55)

Why long baseline interferometry?

- High angular imaging using single telescopes: speckle interferometry, AO direct imaging, and aperture masking.



Keck aperture masking + IOTA observations of a red supergiant + dust shell (Monnier et al. 2004, ApJ 605, 436)

- Aperture masking is the most powerful single aperture technique for bright targets, providing a nice demo of what could eventually be done with long baseline imaging sparse arrays of > 10 apertures. Remains limited to a few tens of objects (>20 mas). See Tuthill et al. 2000, PASP

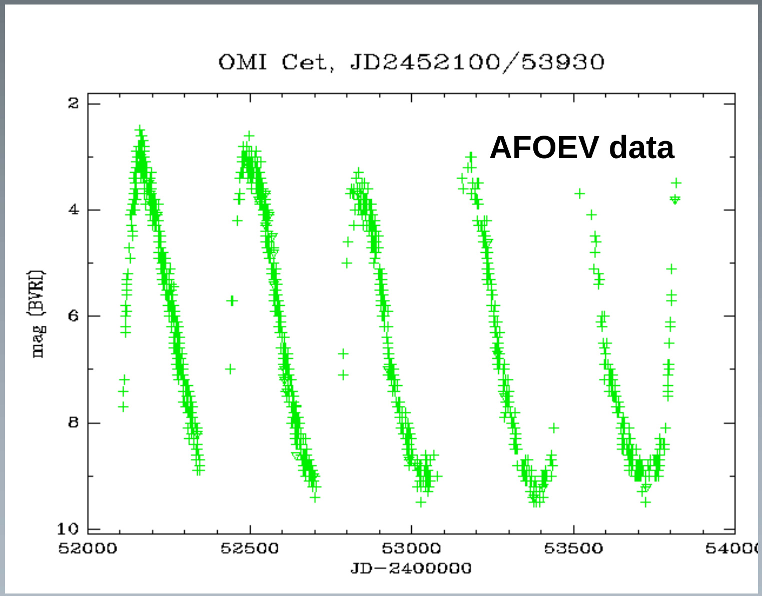
- High fidelity dust shell images can be retrieved when used in conjunction with long baseline interferometric data

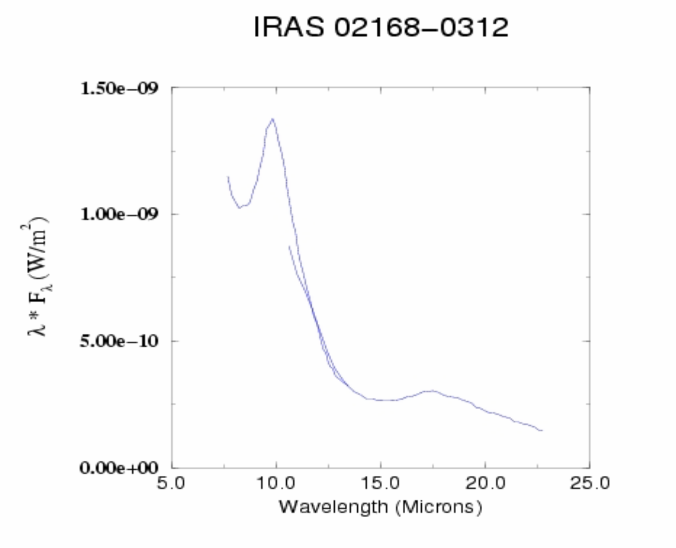
Why long baseline interferometry?

- Statistical survey of a large number of stars requires mas resolution and long baseline interferometry
- Nice complement to spectroscopy and high resolution single aperture techniques: identifies spatial locations of atmospheric features, truly resolves central object
- AO on large telescopes makes interferometers significantly more sensitive in the near IR (R~10000 on AMBER)
- Recent progress: accurate visibility measurements (single-mode interferometry, nulling), accurate phase closure measurements (COAST, NPOI, IOTA, CHARA, VLTI), and future astrometric capabilities (PRIMA)

Miras and semi-regular variable giants: ideal targets for optical interferometry

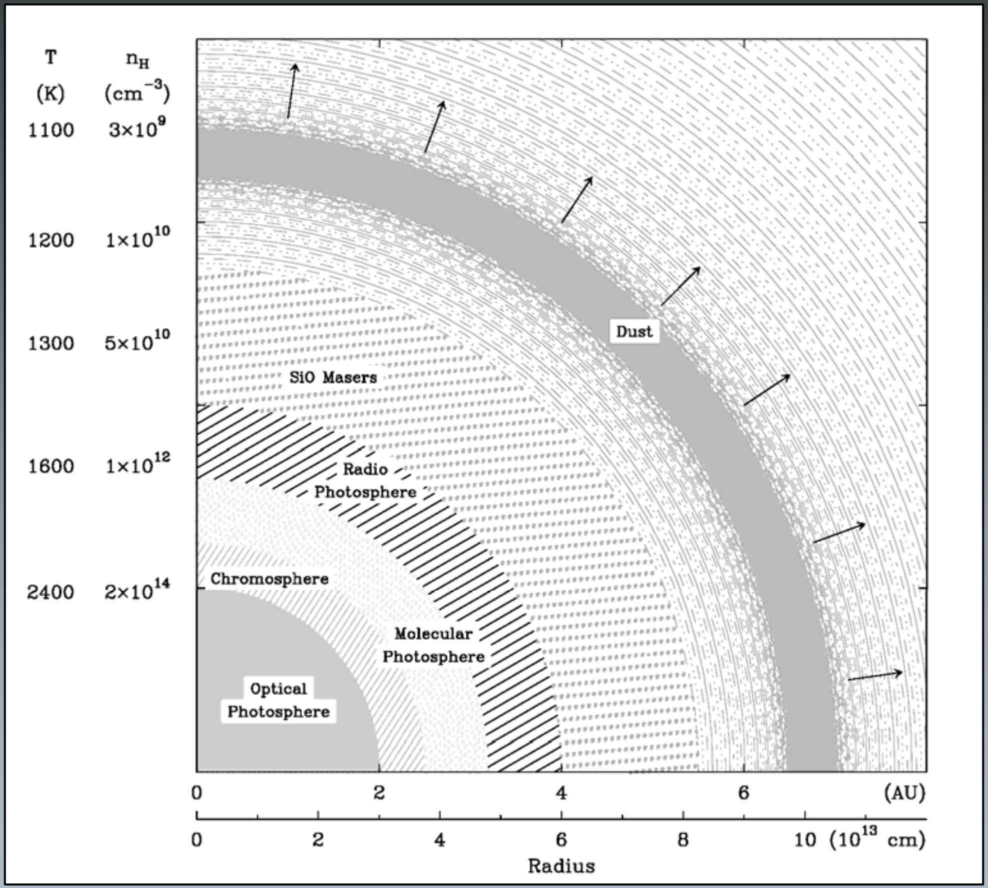
- Extremely bright in the near to mid IR (>500 O-rich and 100 C-rich AGB stars brighter than 1J at 12 microns)
- Very extended (typical sizes of several AUs) and easily resolved
- Visual brightness change x10 to x1000 over periods of 80 -1000 days





- Heavy mass loss rates: ~ 1e-7 to 1e-5 M_{Sun} / yr
- Mid infrared excess due to circum-stellar dust emission

But hard to understand!



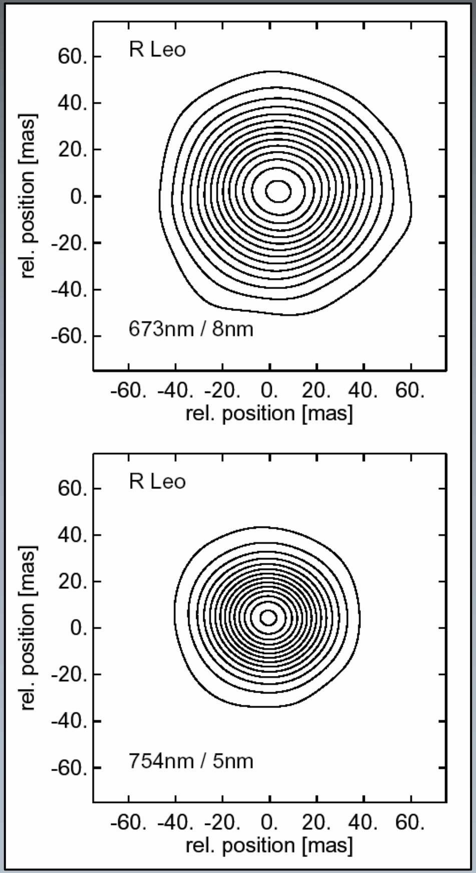
Simplified atmospheric structure of a typical Mira star, from Reid and Menten (1997)

- ✓ Complex and variable structure
- ✓ Chemical nature/ location of molecules and dust layers
- ✓ Source of luminosity variations
- ✓ Size variations or opacity fluctuations?
- ✓ Actual mass loss mechanism / effect of molecular layers

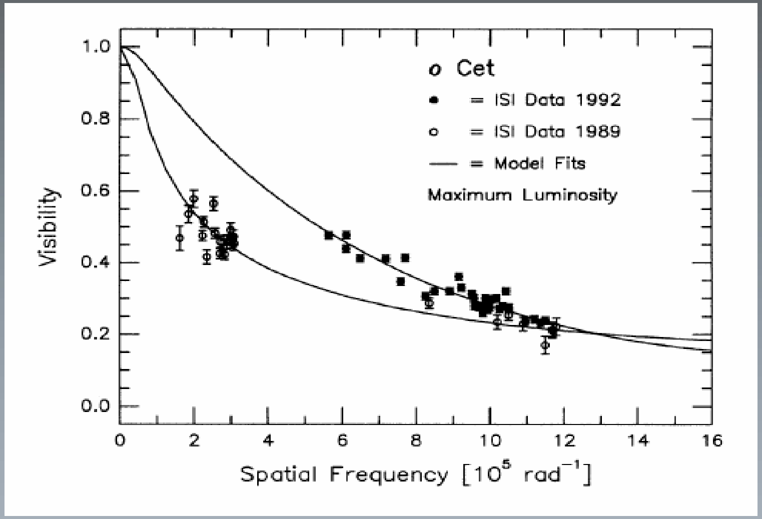
Interpreting interferometric data

- Apparent size variations vs wavelength:

R Leo as seen in and out of TiO bands (Hoffman et al. 2001, A&A)



O Ceti seen by the ISI at 11.15μm (Danchi et al. 1994, AJ)



- Visible: contamination by TiO bands evidenced by long baseline (COAST 1997) and speckle (SAO 6m) interferometry

- Thermal Infrared: effect of dust shells known from ISI

- Hope was that the near IR would provide true photospheric sizes

Interpreting interferometric data

- Apparent size variations vs wavelength: what's going on?!

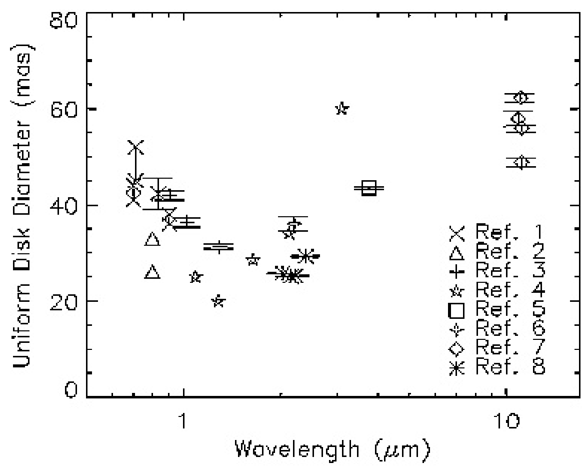
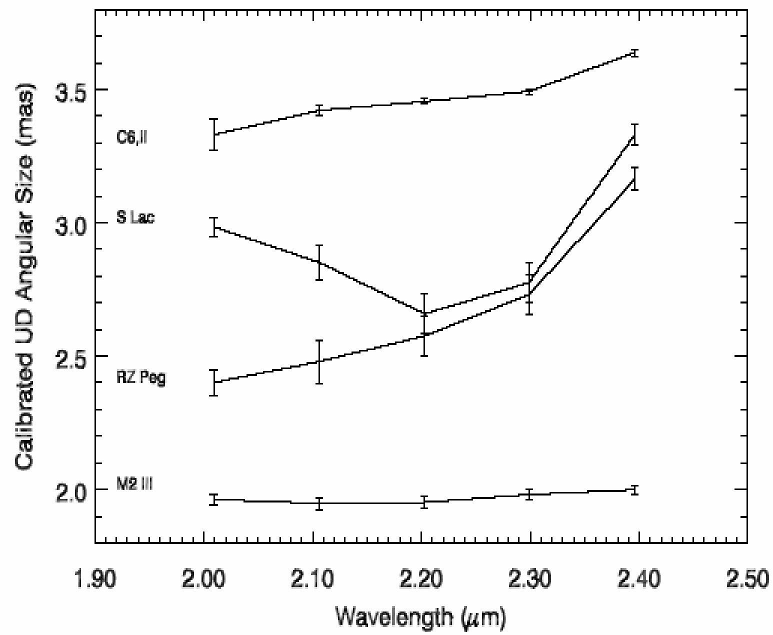


FIG. 1.—Various published uniform disk diameters of *o* Cet: (1) Haniff et al. 1995; (2) Quirrenbach et al. 1992; (3) Young et al. 1999; (4) Tuthill et al. 1999; (5) Mennesson et al. 2000; (6) Ridgway et al. 1992; (7) Weiner et al. 2003; (8) Perrin et al. 2004.

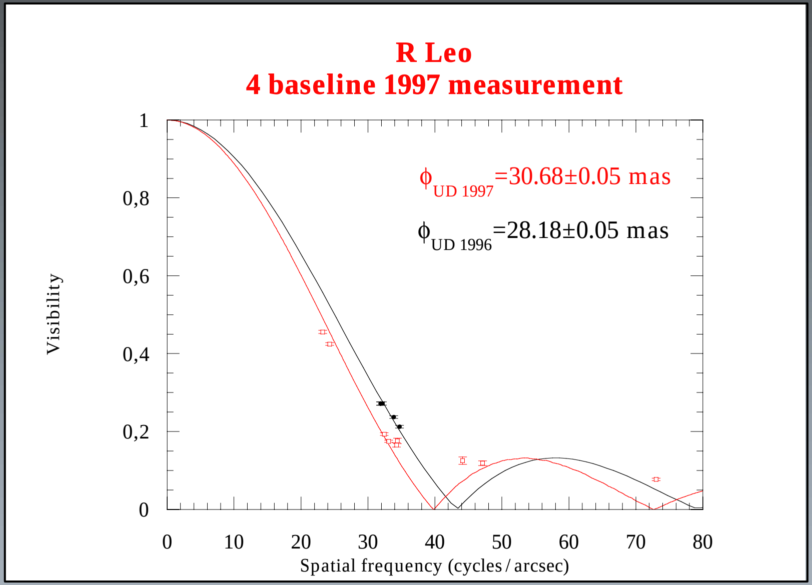
o Ceti UD sizes derived close to maximum phase at different wavelengths (data compiled by J. Weiner 2004, ApJ, 611, L37)

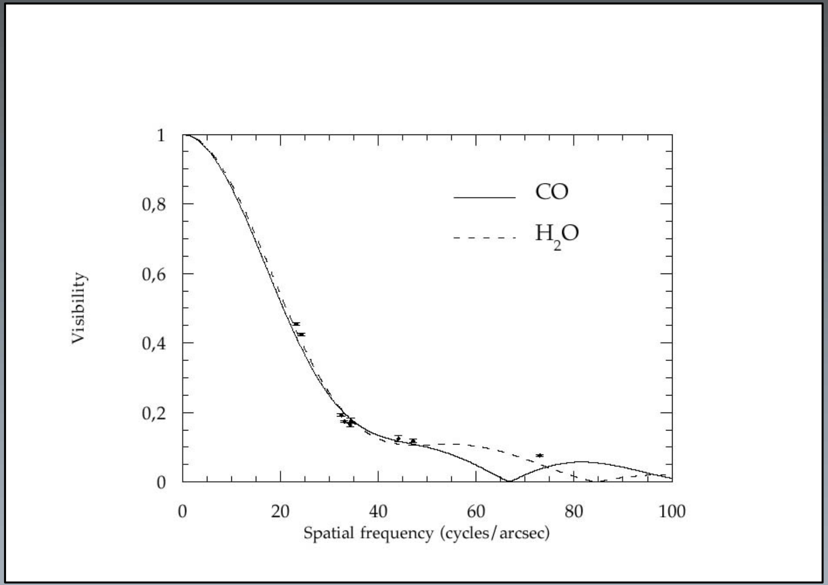


Apparent UD sizes inside the K band for representative O-rich and C-rich Miras. (from Thompson et al. 2002 ApJ 577, 447)

Interpreting Visibilities

- A closer look a the CLV (R Leo, Perrin et al. 1999, K band)





Fit using model restricted to molecular bands developed by Scholz & Takeda 1987

The surprise of the L band observations of O-rich Miras and semi-regular variables

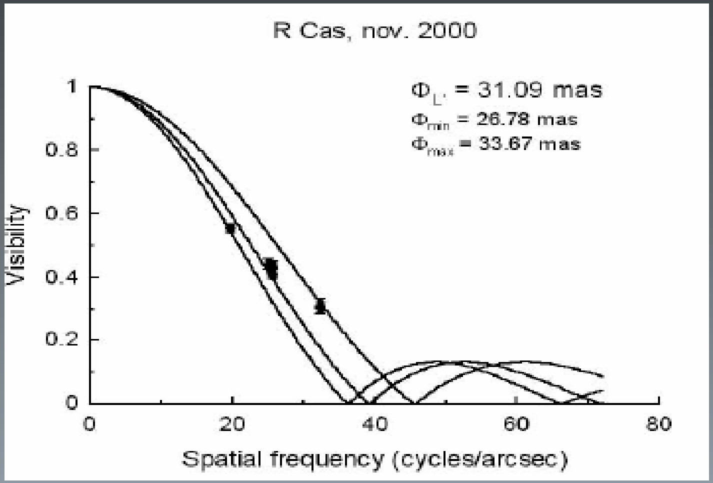
(IOTA/TISIS Mennesson et al. 1998-2000)

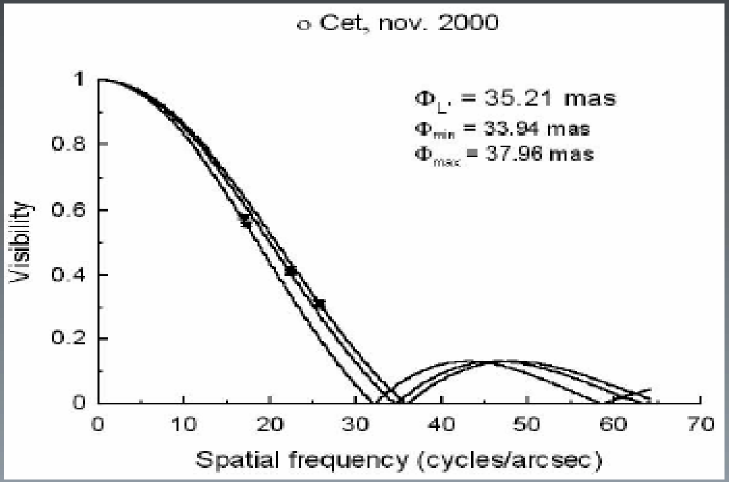
- Apparent UD size increases of 20 to 100% between K and L' broad-band measurements at ~same phase

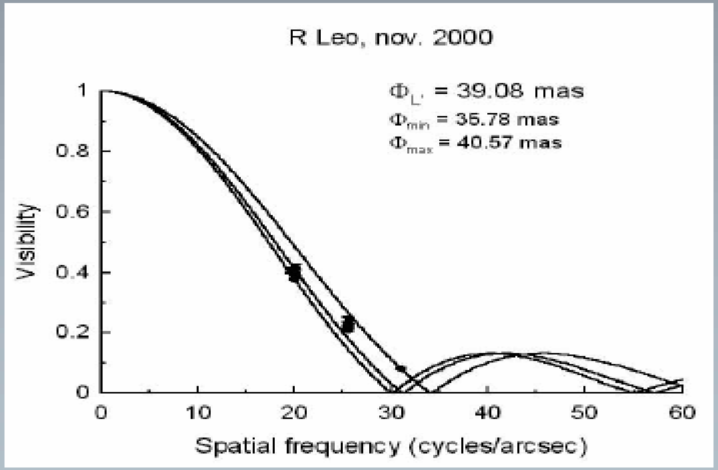
Physical Properties of Mira Variables and Semiregular Variable Stars Observed with FLUOR/TISIS

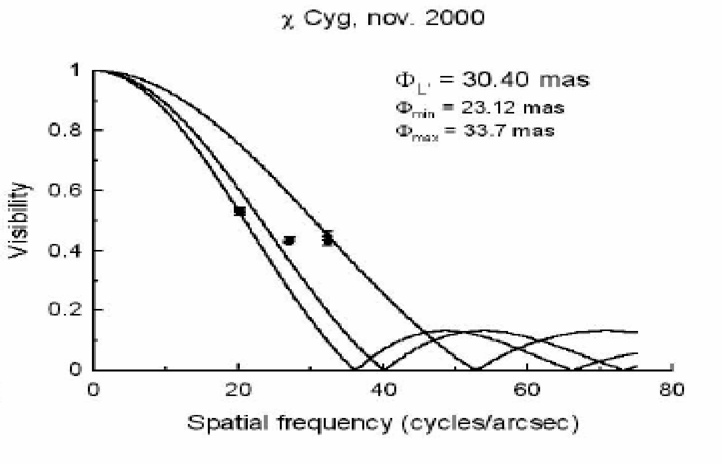
Star	Period (days)	[12] – [25]	dM/dt ($M_\odot$ yr^{-1})	Δm_V	Phase	$\phi_{L'}/\phi_{K'}$
R Aquarii	387	0.40	3.0 10^{-7}[a]	5	0.46 ± 0.05	$2.03^{+0.14}_{-0.12}$
R Cassiopeiae	431	0.60	1.1 10^{-6}[b]	7	0.13 ± 0.04	1.25 ± 0.01
U Herculis	405	0.45	2.6 10^{-7}[b]	6.5	0.25 ± 0.02	1.30 ± 0.05
χ Cygni	408	0.15	5.6 10^{-7}[b]	8.5	0.59 ± 0.22	1.31 ± 0.01
R Cancri	362	0.49	2.0 10^{-8}[a]	5	0.36 ± 0.02	1.43 ± 0.04
					0.01 ± 0.05	1.33 ± 0.12
R Leonis Minoris	372	0.60	2.8 10^{-7}[b]	5.5	0.03 ± 0.05	2.04 ± 0.05
U Orionis	372	0.51	3.0 10^{-7}[a]	6.5	0.92 ± 0.04	1.65 ± 0.02
o Ceti	332	0.72	5.0 10^{-7}[a]	7	0.06 ± 0.05	1.44 ± 0.01
R Leonis	310	0.26	1.0 10^{-7}[b]	5.5	...	1.28 ± 0.11
SW Virginis	150	0.81	5.7 10^{-7}[b]	2.5	...	1.41 ± 0.02
RT Virginis	...	0.77	7.4 10^{-7}[b]	1	...	1.31 ± 0.06
RX Bootis	195	0.80	8.1 10^{-7}[b]	1.5	...	1.20 ± 0.01
g Herculis	89	0.39	2.6 10^{-7}[b]	1	...	1.64 ± 0.05
RS Cancri	120	0.66	5.2 10^{-7}[b]	1.5	...	$1.28^{+0.33}_{-0.27}$

UD models provide bad fits for most Miras L' observations



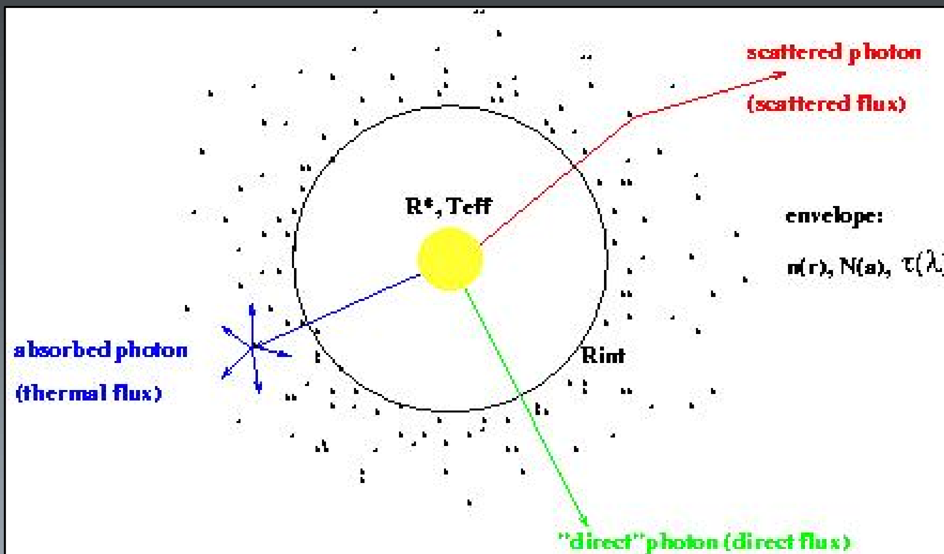


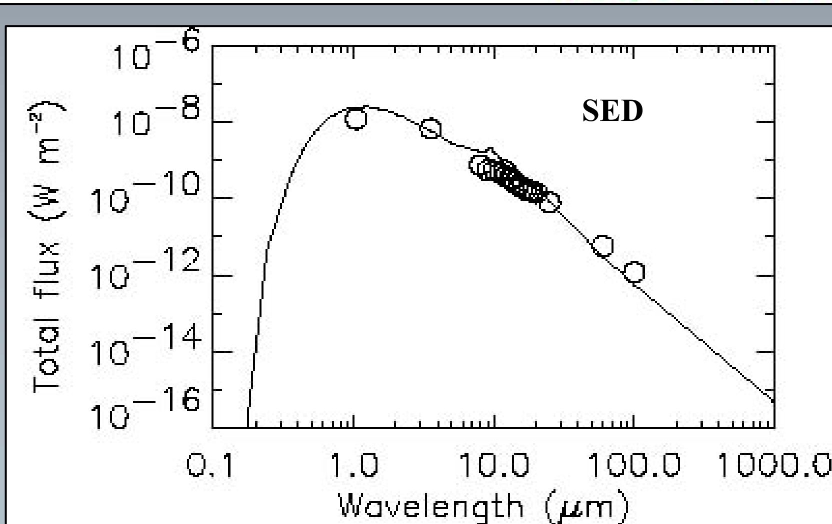


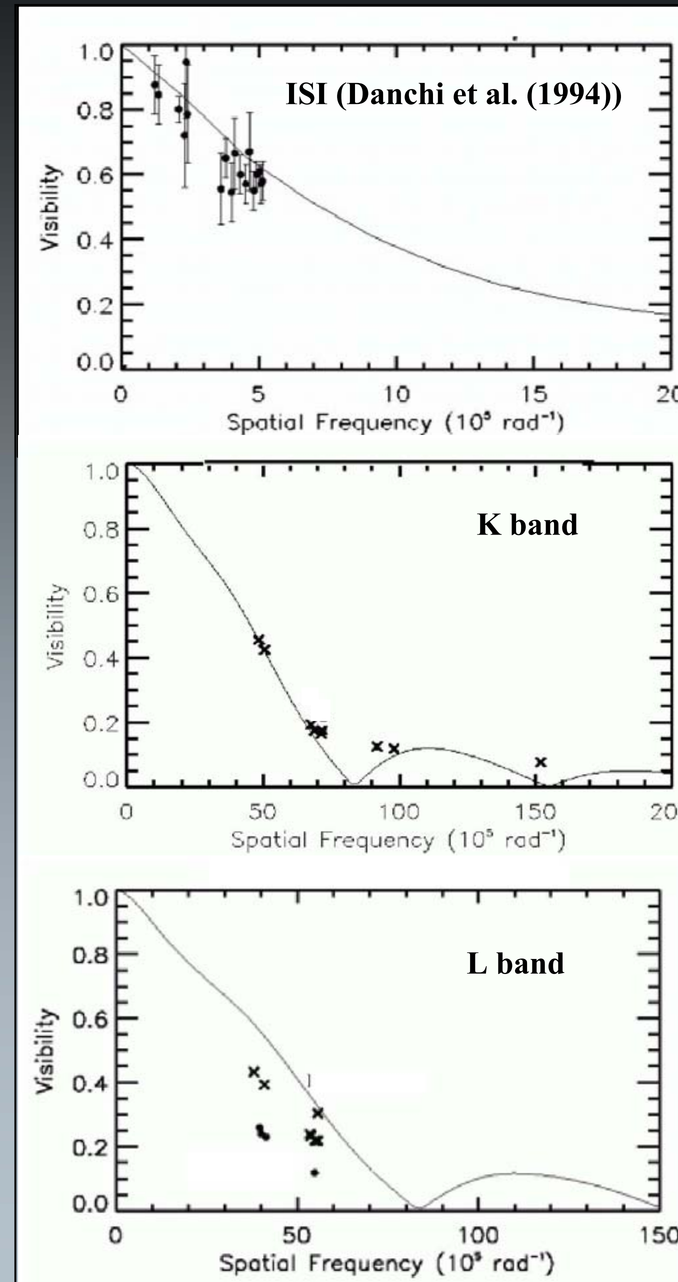


Dust alone can not explain it

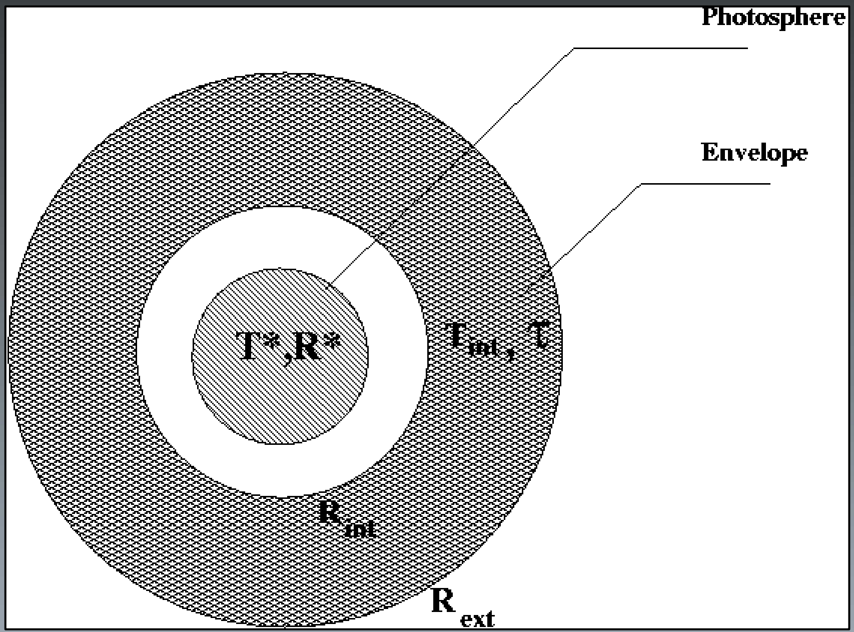
(Schuller et al. 2004, Benson et al. 2003)

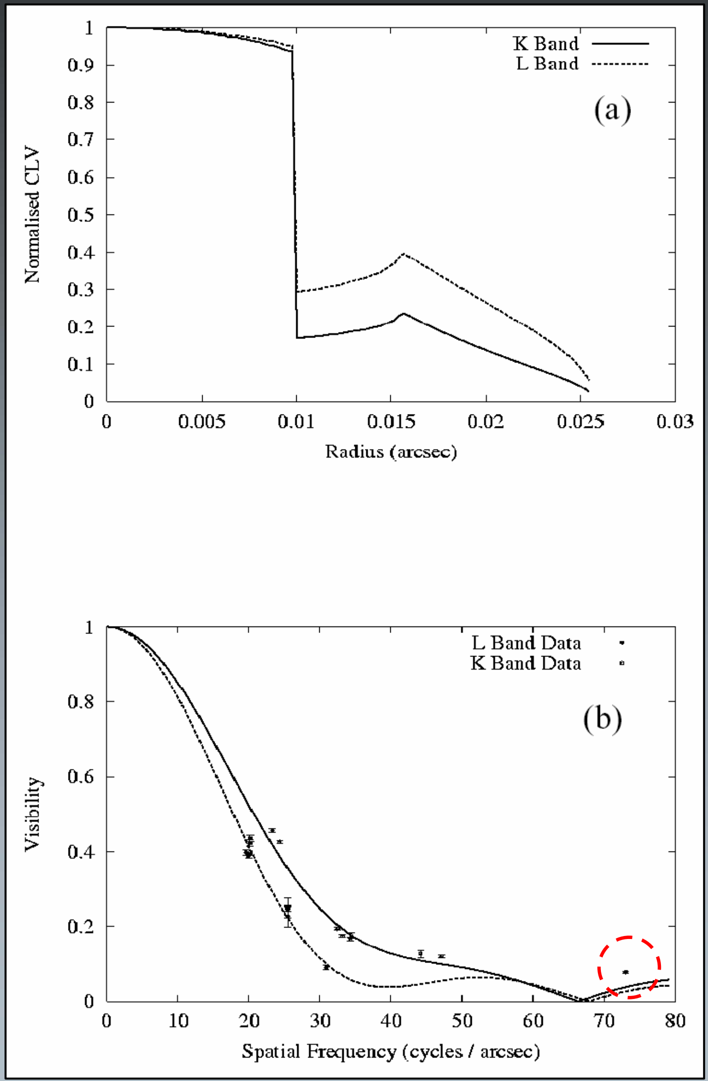






K and L' observations: the nearby extended layer scenario (Mennesson et al. 2002)





<u>R Leo main parameters :</u>

$R_* = 10$ mas

$T_* = 2700$ K

$\tau = 0{,}5$

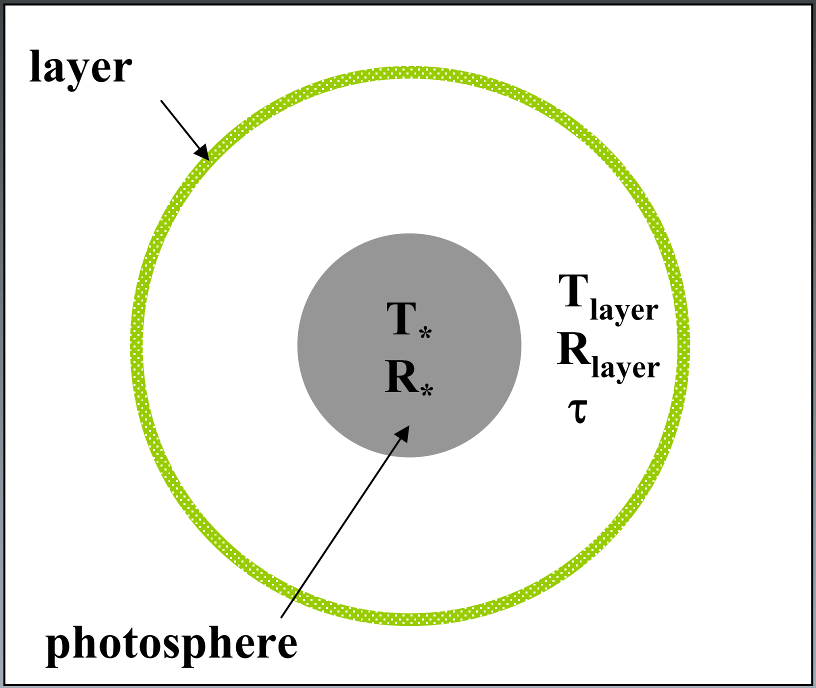
$R_{in} = 15$ mas

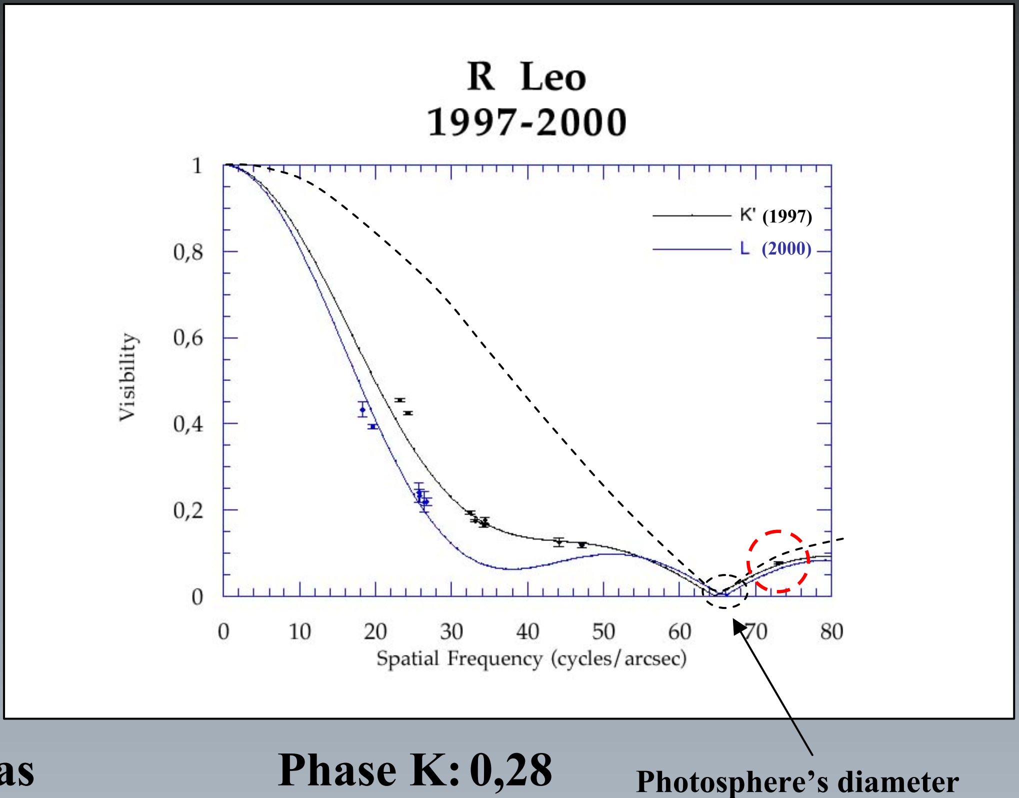
$R_{out} = 27$ mas

$T_{in} \leq 1730$ K

Simplified model : photosphere + thin layer

(Perrin et al. 2004)



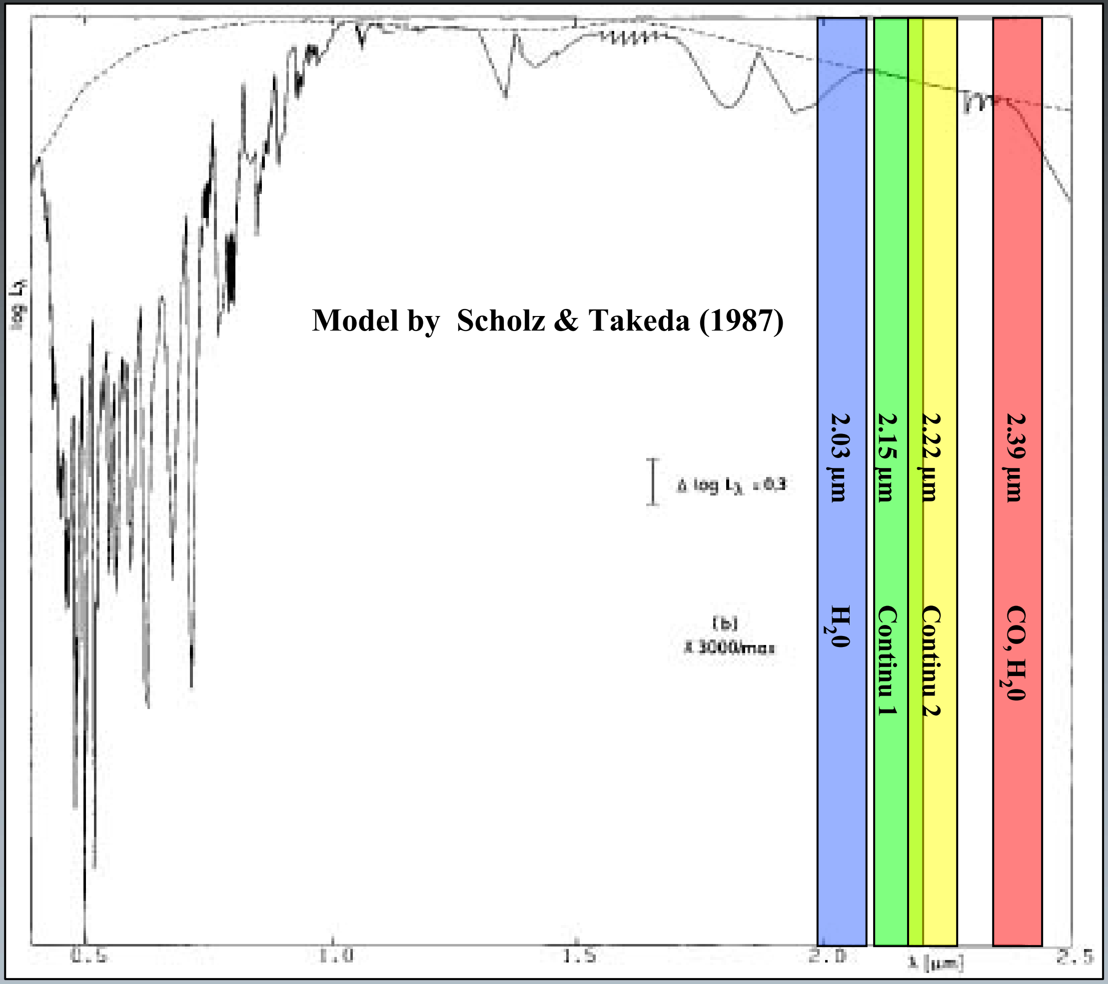


$R_* = 10{,}5$ mas
$T_* = 2700$ K
$\tau_K = 1{,}04$
$\tau_L = 0{,}81$

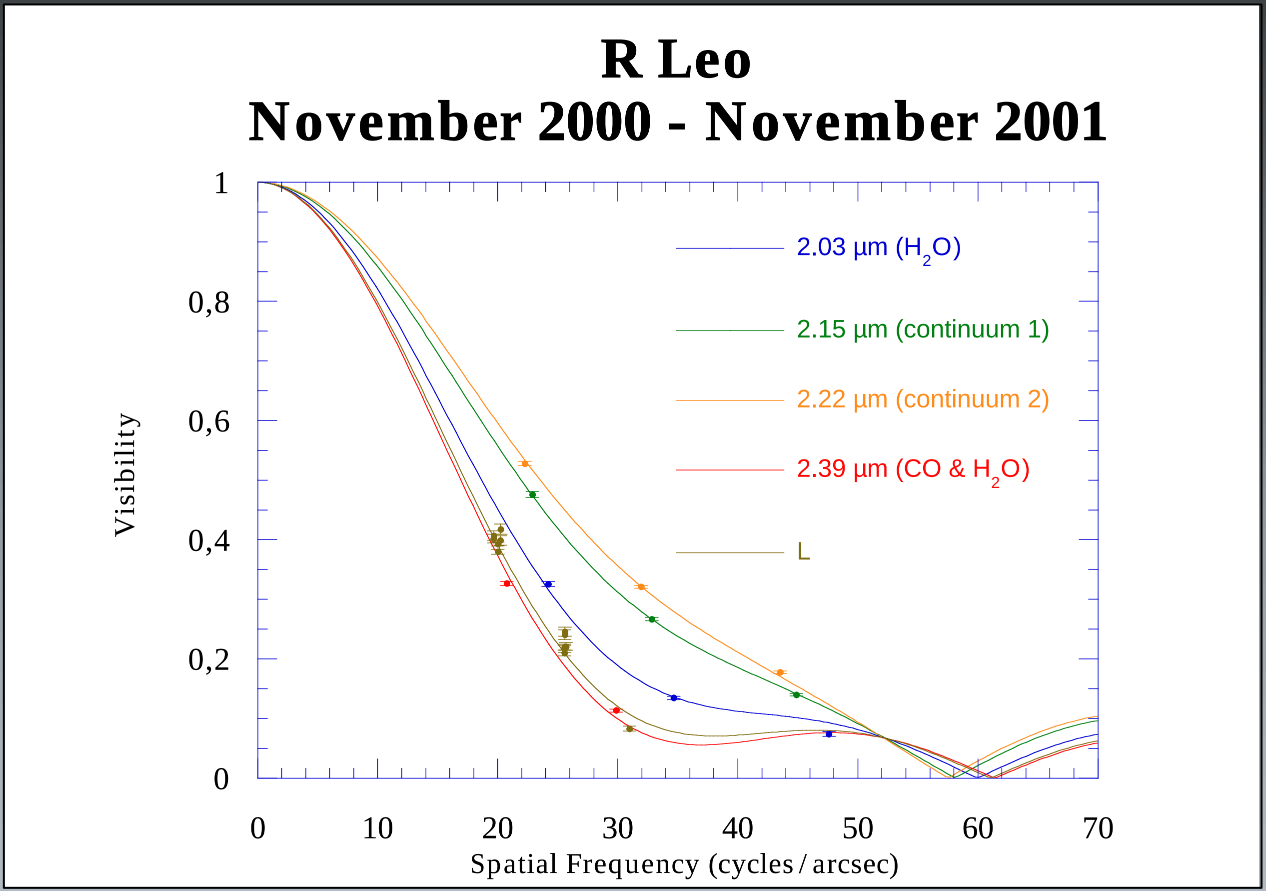
$R_{layer} = 23{,}7$ mas
$T_{layer} = 1300$ K

Phase K: 0,28
Phase L: 0,81

K narrow band observations



Fitting R Leo K narrow-band and L broad-band data (Perrin et al. 2004)



$\tau_{2.03\mu m} = 1,19 \pm 0,01$

$\tau_{2.15\mu m} = 0,51 \pm 0,01$

$\tau_{2.22\mu m} = 0,33 \pm 0,01$

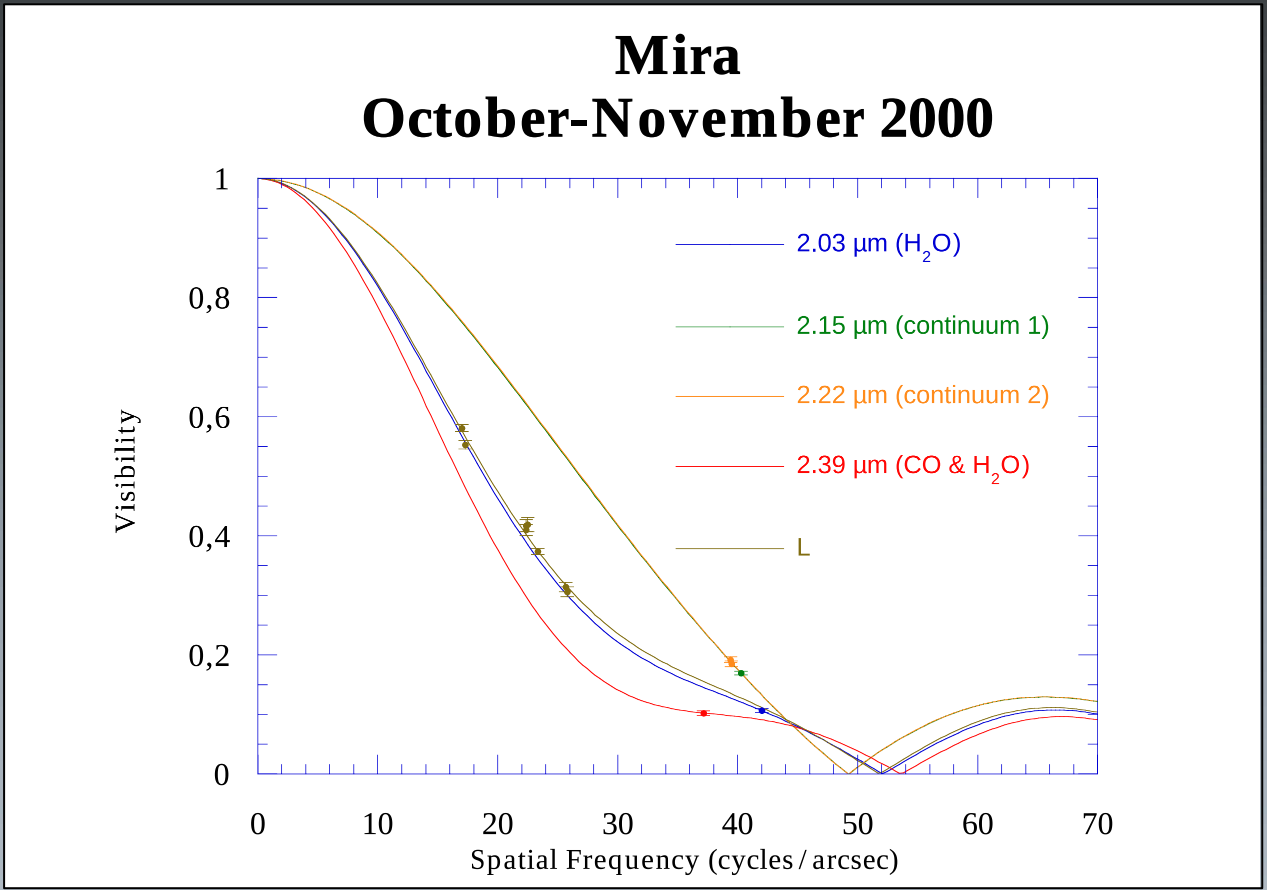
$\tau_{2.39\mu m} = 1,37 \pm 0,01$

$\tau_{L} = 0,63 \pm 0,01$

$R_* = 10,94 \pm 0,85$ mas **$R_{layer} = 25,00 \pm 0,17$mas** **Phase K: 0,79** **Type: M0-M1**

$T_* = 3856 \pm 119$ K **$T_{layer} = 1598 \pm 24$ K** **Phase L: 0,64**

Fitting Mira's K narrow-band and L broad-band 2000 data (Perrin et al. 2004)



$\tau_{2.03\mu m} = 0{,}14 \pm 0{,}02$

$\tau_{2.15\mu m} = 0{,}01 \pm 0{,}01$

$\tau_{2.22\mu m} = 0{,}01 \pm 0{,}01$

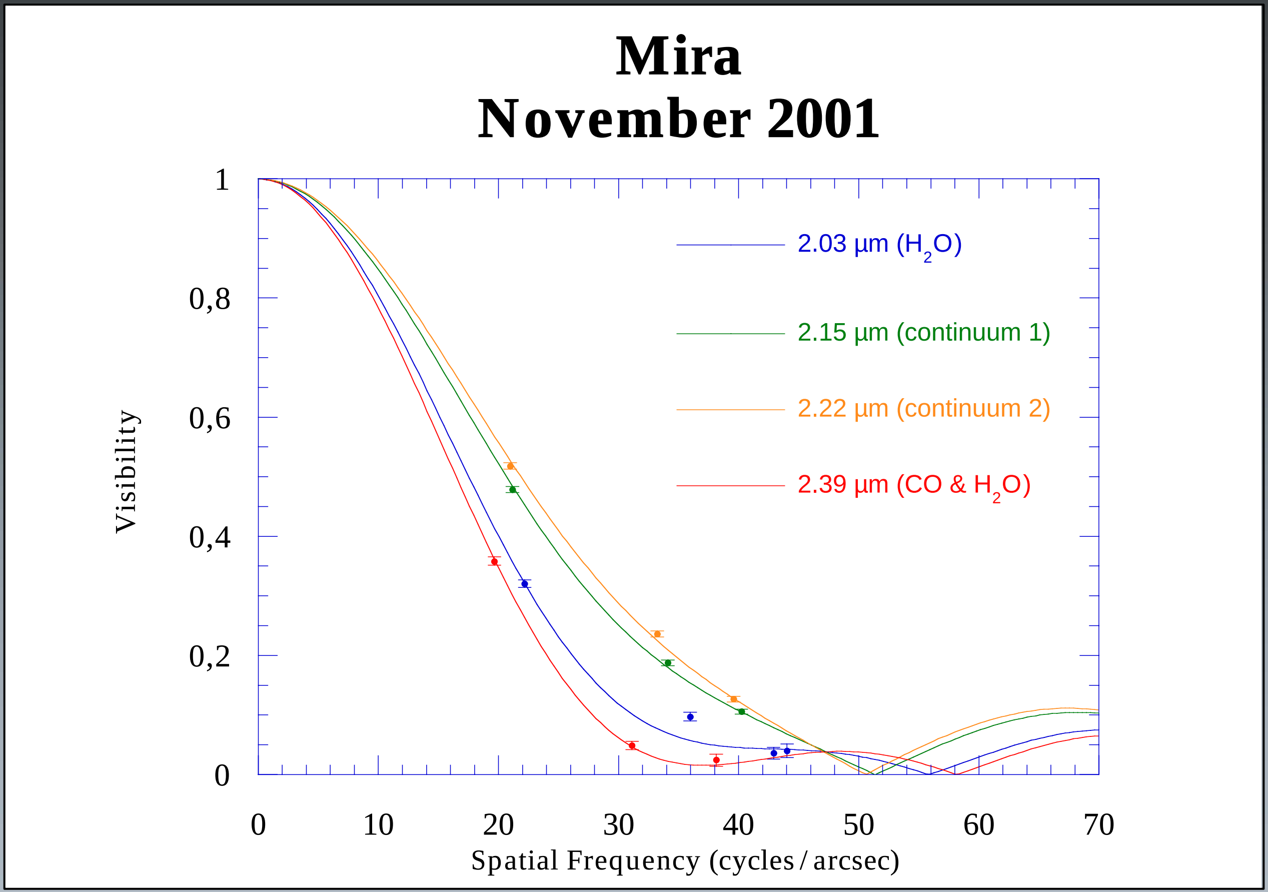
$\tau_{2.39\mu m} = 0{,}21 \pm 0{,}01$

$\tau_{L} = 0{,}08 \pm 0{,}01$

$R_* = 12{,}29 \pm 0{,}02$ mas **$R_{layer} = 26{,}84 \pm 0{,}06$ mas** **Phase K: 0,01** **Type: M6**

$T_* = 3263 \pm 105$ K **$T_{layer} = 2105 \pm 53$ K** **Phase L: 0,10**

Fitting Mira's K narrow-band and L broad-band 2001 data



$\tau_{2.03\mu m} = 0{,}63 \pm 0{,}21$

$\tau_{2.15\mu m} = 0{,}19 \pm 0{,}05$

$\tau_{2.22\mu m} = 0{,}12 \pm 0{,}04$

$\tau_{2.39\mu m} = 0{,}76 \pm 0{,}50$

$R_* = 12{,}71 \pm 0{,}15$ mas **$R_{layer} = 24{,}95 \pm 0{,}10$ mas** **Phase: 0,19** **Type: M3-M4**

$T_* = 3600 \pm 67$ K **$T_{layer} = 1961 \pm 17$ K**

Comparing Mira at phases 0 and 0.2

Phase 0 (October 2000)

R_* = 12,29±0,02 mas R_{layer} = 26,84±0,06 mas

R_* ↗ 0,37 mas (3%)

Phase 0,2 (November 2001)

R_* = 12,71±0,15 mas R_{layer} = 24,95±0,10 mas

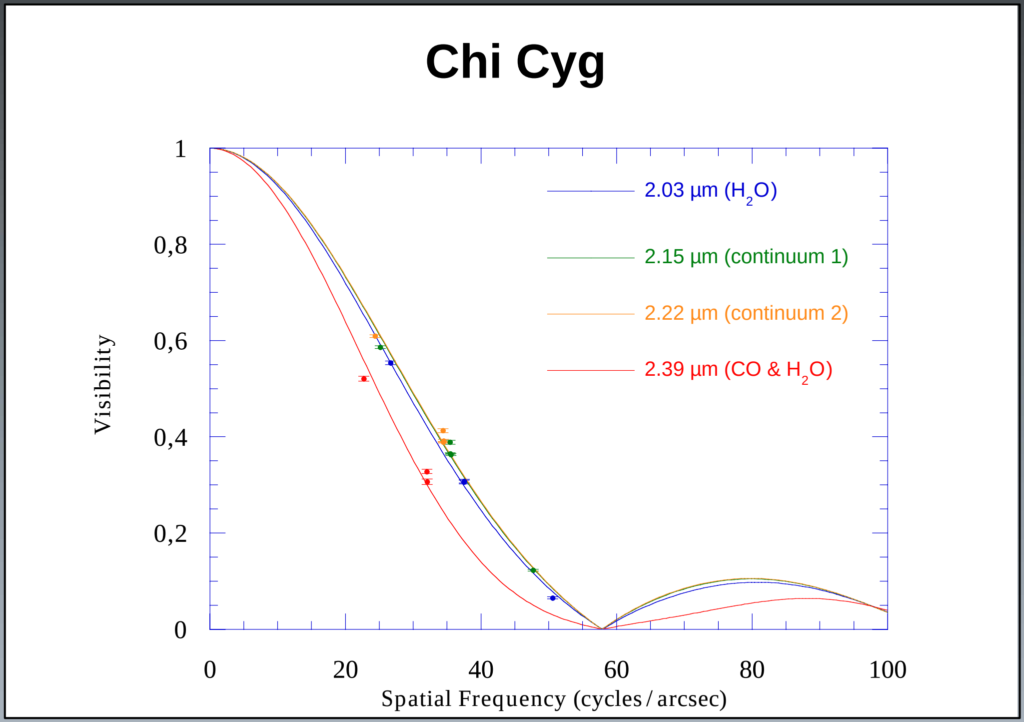
R_{layer} ⬃ 1,89 mas (7.3%)

Although the change in *apparent* diameter is over 20% !!

Phase 0	Phase 0,2
$\tau_{2.03\mu m}$ = 0,14±0,02	$\tau_{2.03\mu m}$ = 0,63±0,21
$\tau_{2.15\mu m}$ = 0,01±0,01	$\tau_{2.15\mu m}$ = 0,19±0,05
$\tau_{2.22\mu m}$ = 0,01±0,01	$\tau_{2.22\mu m}$ = 0,12±0,04
$\tau_{2.39\mu m}$ = 0,21±0,01	$\tau_{2.39\mu m}$ = 0,76±0,50

Most of the visibility variation is likely caused by a change in opacity

Probing the chemical content of the layer: the case of an S star



$\tau_{2.03\mu m} = 0.21 \pm 0.01$

$\tau_{2.15\mu m} = 0.14 \pm 0.01$

$\tau_{2.22\mu m} = 0.12 \pm 0.01$

$\tau_{2.39\mu m} = 0.54 \pm 0.03$

$R_* = 10.55 \pm 0{,}01$ mas   **$R_{layer} = 18.78 \pm 0{,}06$ mas**   **Phase: 0,24**

$T_* = 3312 \pm 158$ K   **$T_{layer} = 1685 \pm 53$ K**

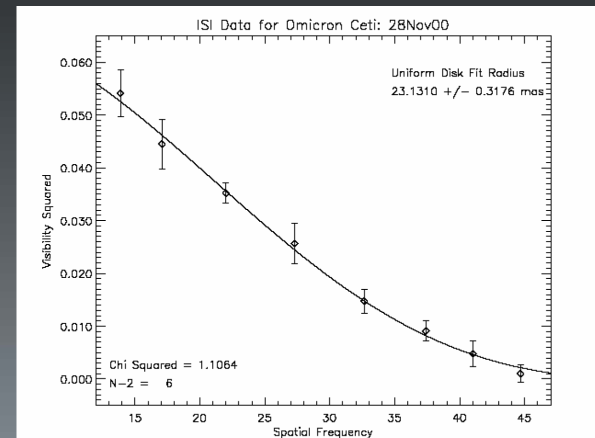
Summary of molecular layer characteristics

Star	Phase	$R_{\text{layer}}/R_\star$	T_{layer} (K)
Mira	0.01	2.2	2100
Mira	0.20	2.0	2000
T Cep	0.67	2.2	1700
R Leo	0.80	2.3	1600
U Ori	0.83	2.4	1500
U Ori	0.91	2.5	1900
χ Cyg	0.24	1.8	1700
χ Cyg	0.76	1.9	1700

Comparing to ISI 11.15 μm data

- V measurements resolving cold outer dust, then probably seeing the same “molsphere” as in the near IR, but with a different opacity

$$V(x,r,A) = \frac{2AJ_1(2\pi rx)}{2\pi rx}$$



Result of multi-λ fit using explicit H_2O cross sections (Weiner 2004, ApJ):

BEST-FITTING H_2O SHELL MODEL PARAMETERS

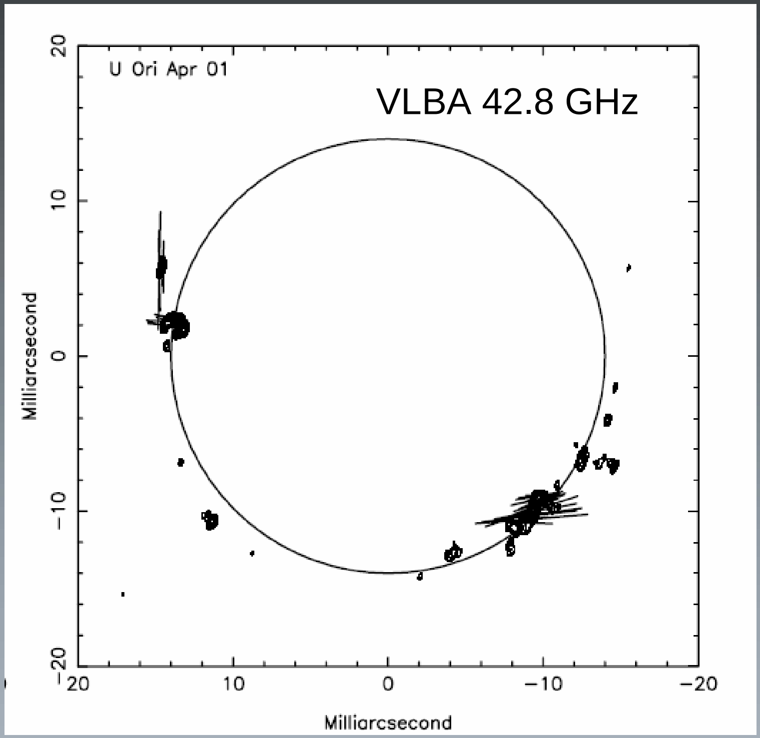
Parameter	Value
R_*	12.78 mas
T_*	2701 K[a]
R_{H_2O}	30.32 mas
T_{H_2O}	2200 K
N_c	7.047×10^{19} cm^{-2}
A_{dust}	0.7214

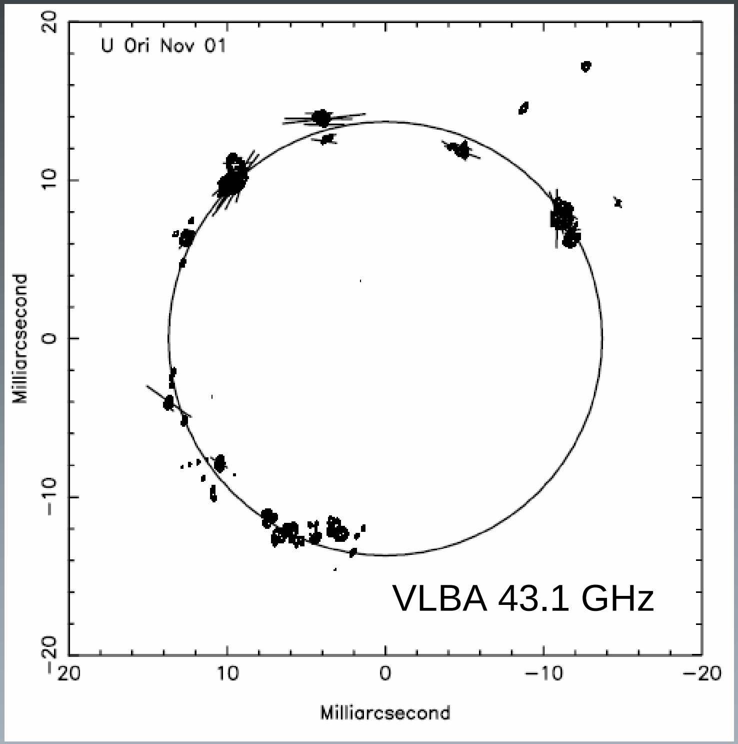
Result from narrow K and L band data (Perrin et al. 2004, A&A):

Year	2000	2001
$R_\star$ (mas)	12.29 ± 0.02	12.71 ± 0.15
R_{layer} (mas)	26.84 ± 0.06	24.95 ± 0.10
$T_\star$ (K)	3263 ± 105	3600 ± 67
T_{layer} (K)	2105 ± 53	1961 ± 17
$\tau_{2.03}$	0.14 ± 0.02	0.63 ± 0.21
$\tau_{2.15}$	0.01 ± 0.01	0.19 ± 0.05
$\tau_{2.22}$	0.01 ± 0.01	0.12 ± 0.04
$\tau_{2.39}$	0.21 ± 0.01	0.76 ± 0.50
$\tau_{L'}$	0.08 ± 0.01	

Comparing to closest MASERs location (SiO)

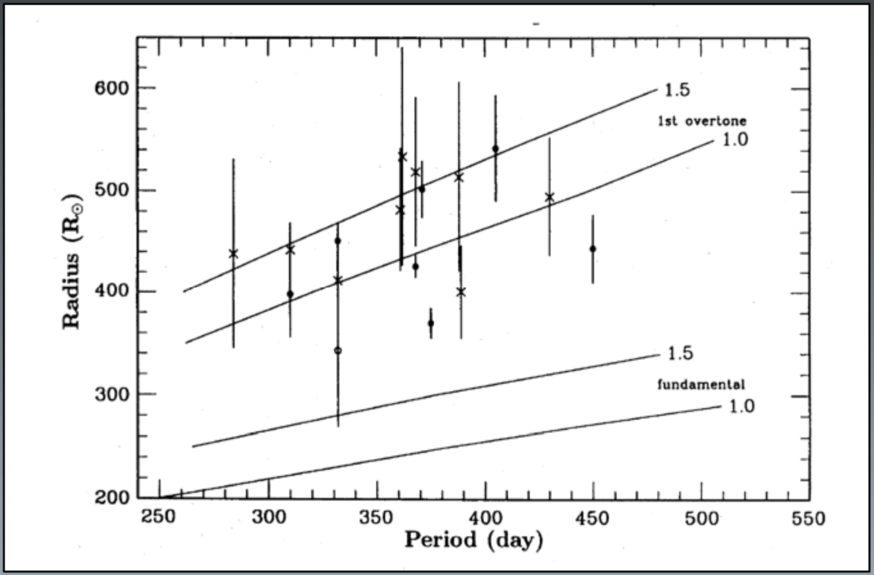
(Cotton et al. 2004)



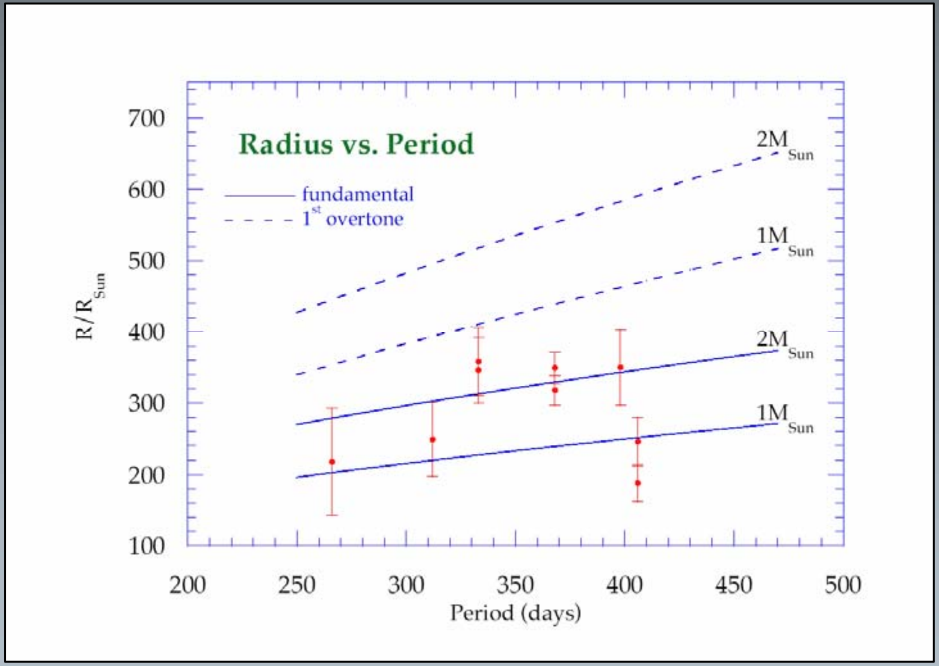


Star	$R_{\rm layer}$ (mas)	$R_{\rm SiO}$ (mas)	$R_{\rm SiO}/R_{\rm layer}$
R Leo	25.00	30.6	1.22
Mira	24.95	37.8	1.52
U Ori	12.00	14.4	1.20

Radius and pulsation mode of Miras



(Feast 1996)



Some conclusions on O-rich Miras

UD models are from the past and of little use

Simple model with photosphere surrounded by a spherical thin molecular layer of H_2O and CO can reproduce observational diversity from the visible to the mid IR

Molsphere scenario also consistent with spectroscopic measurements and SiO masers observations

Interest of disentangling the photospheric size variations from opacity effects

Smaller photospheric diameters, hotter Teff (~3000-3500K), fundamental mode of pulsation

Role of molecular layer: cool down the stellar environment allowing dust to form closer, and radiation pressure to be more efficient in driving the gas out (collisional coupling with dust)

More elaborate models needed for interpretation beyond 1^{st} order effects

Some remaining issues for O-rich Miras

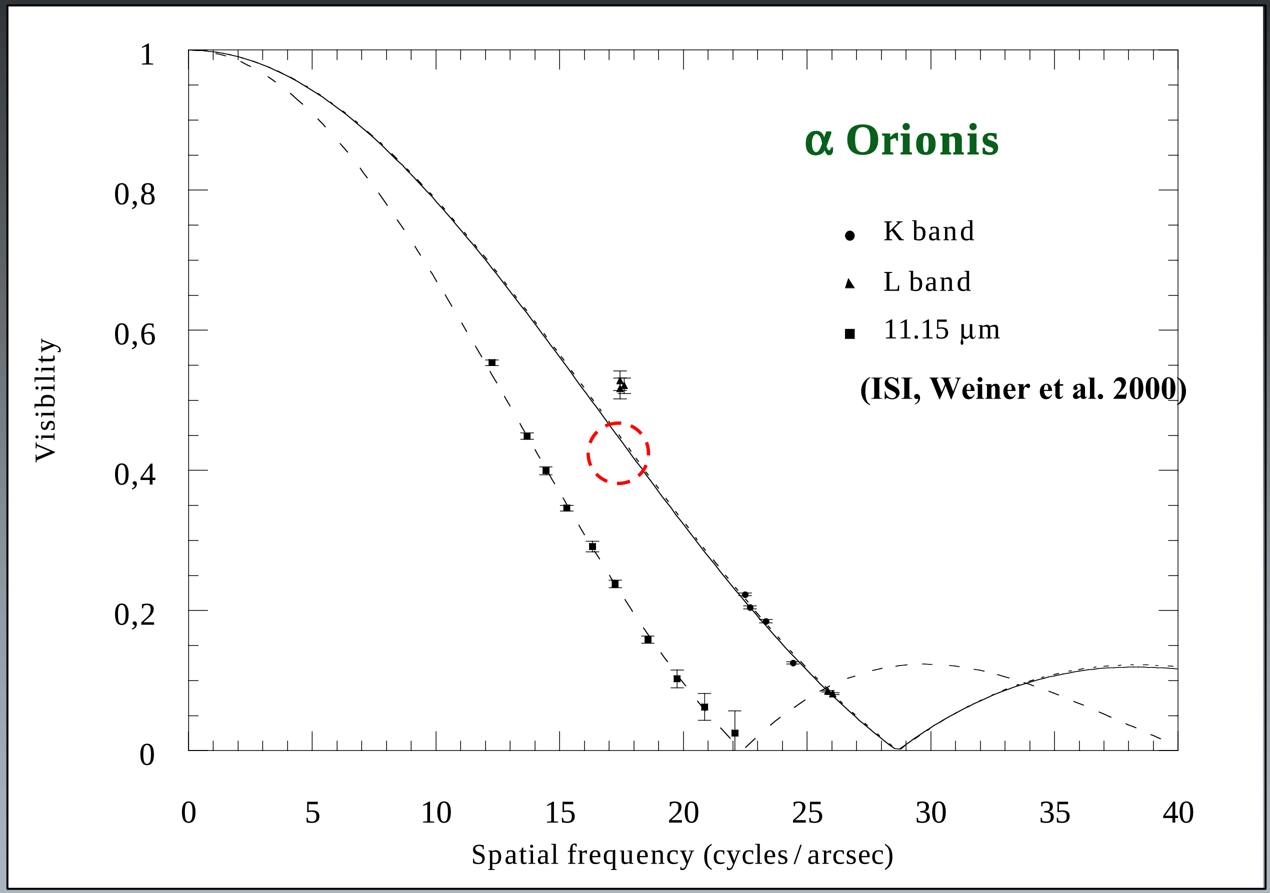
- Geometrically thin layer scenario is very schematic
- High resolution mid IR spectra show no salient H_2O features: only partially explained by filling-in effect (emission from outer H_2O layer, Ohnaka 2004). Points to extended layers than geometrically thin…
- Extended warm water vapor envelope created by large amplitude pulsation dynamic models (Ohnaka, Scholz & Wood 2006) is slightly smaller than observed in the case of o Ceti

Model	Cycle+Phase	$R_{1.04}/R_p$	T_{eff} (K)	$T_{1.04}$ (K)	L ($L_\odot$)
P23n	2+0.30	1.24	2470	2590	3570

(N.B. Rp*=241RSun → Rp*= 10.5 mas @ 107pc, vs R*=12.5 mas from IOTA/FLUOR/ISI)

- More refined dynamical models including dust formation needed

Application to Red Supergiants: α Ori



(Perrin et al. A&A 2004)

$\varnothing_\star = 42.00 \pm 0.06\,\mathrm{mas}$, $T_\star = 3690 \pm 50\,\mathrm{K}$

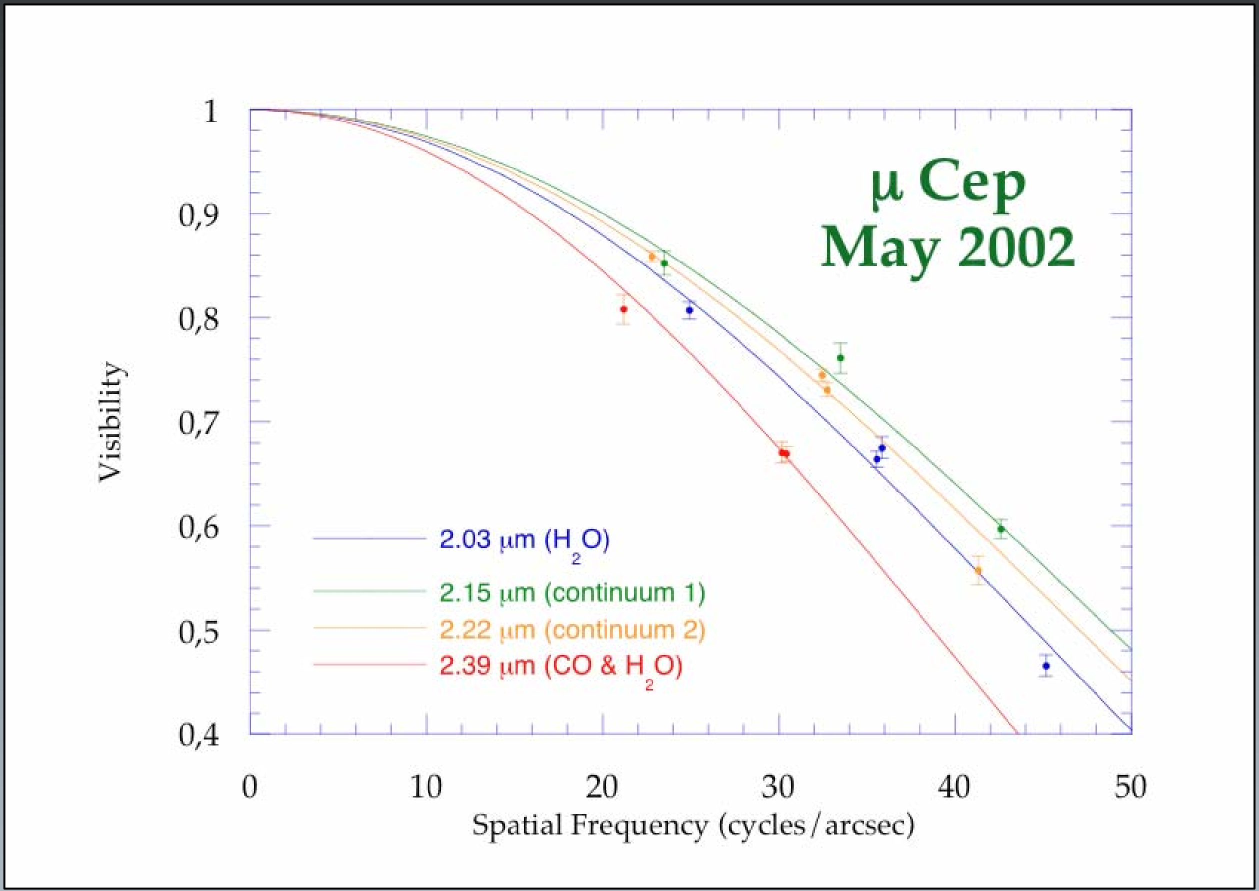
$\varnothing_{\mathrm{layer}} = 55.78 \pm 0.04\,\mathrm{mas}$, $T_{\mathrm{layer}} = 2055 \pm 25\,\mathrm{K}$

$\tau_K = 0.060 \pm 0.003$

$\tau_L = 0.026 \pm 0.002$

$\tau_{11.15\mu m} = 2.33 \pm 0.23$

Application to Red Supergiants: μ Cep



(Perrin et al. 2005)

$\tau_{2.03\mu m}$ = 0,22±0,03

$\tau_{2.15\mu m}$ = 0,02±0,01

$\tau_{2.22\mu m}$ = 0,07±0,01

$\tau_{2.39\mu m}$ = 3,92±1,58

R_* = 7,06±0,30 mas **R_{layer} = 9,28±0,13mas**

T_* = 3789±100 K **T_{layer} = 2684±100 K**

Mozurkewich et al. (2003) :
R_{*800nm} = 9,34 ± 0,22 mas

Comparison μ Cep / α Ori

From IOTA/FLUOR:

Star	Sp	T_* (K)	T_{layer} (K)	R_{layer}/R_*
Betelgeuse	M2 Iab	3690±50	2055±25	1,33
μ Cep	M2 Iae	3789±100	2684±100	1,32

From ISO /Stratoscope II and FLUOR (Tsuji 2006 ApJ)

Star	Sp	T_* (K)	T_{layer} (K)	R_{layer}/R_*
Betelgeuse	M2 Iab	3690±50	2250	1,3
μ Cep	M2 Iae	3789±100	1600	2

Some remaining issues for Supergiants

- How does the warm and dense molecular layer form in the upper atmosphere of supergiants, without any pulsation?
- Role of the chromosphere in that context?
- See Tsuji 2006, ApJ 645, 1448

Molecules around Miras, SR giants and Supergiants: similarities & differences

- Miras and SR giants: $R_{layer} \sim 2R^*$
- SR supergiants: $R_{layer} \sim 1.3R^*$
- Molecular region also exists around stars with moderate or no significant mass loss, but is less extended

Dust characterization via mid infrared interferometry of AGB stars

- Early results from the ISI: narrow band, >100 Jy stars, 13m baseline

Star	Phase	r_0 ($''$)	r_0/r_*	T_0 (K)	τ_{11}	Maser SiO	Maser H_2O	Maser OH
Dust far from star								
α Sco	—	1.0	52	320	1.1(-2)	N	N	N
α Ori	—	1.0	46	400	6.5(-3)	N	N	N
α Her	—	0.25	18	520	1.6(-2)	N	N	N
χ Cyg	min	0.30	19	450	4.3(-2)	Y	N	N
U Ori	max	0.08	11	540	9.2(-2)	Y	Y	Y
W Aql	max	0.07	8.1	1100	7.8(-2)	Y	N	N
Dust close to star								
IRC +10216	max	0.09	2.4	1360	1.2(-0)	Y	N	N
	min	0.07	1.9	1030	1.4(-0)			
R Leo	min	0.07	2.7	790	1.0(-1)	Y[a]	Y	Y
o Cet	max	0.06	3.0	1280	1.4(-1)	Y	Y	N
	min	0.06	3.0	1060	1.4(-1)			
VX Sgr	min	0.06	4.6	720	5.6(-1)	Y	Y	Y
VY CMa	max	0.05	5.3	1560	2.9(-0)	Y	Y	Y
	min	0.04	4.2	1360	2.9(-0)			
IK Tau	max	0.05	5.5	990	1.7(-0)	Y	Y	Y
R Aqr	min	0.07	6.8	530	2.3(-1)	Y	N	N

- What defines the 2 populations: episodic vs continuous dust production or other mechanism?

- Segregation by dust composition and initial core metallicity?

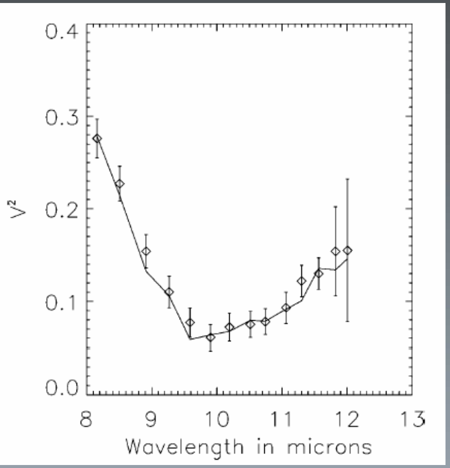
- Recent models (e.g. Ireland and Scholz 2006) can keep Mg-rich dust condensates within 2-3 R*

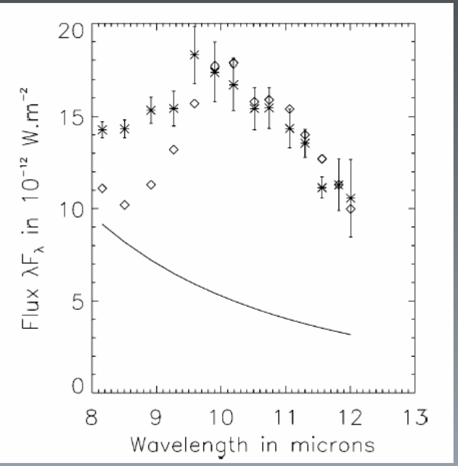
- Can dust really condensate at 2-3R*??

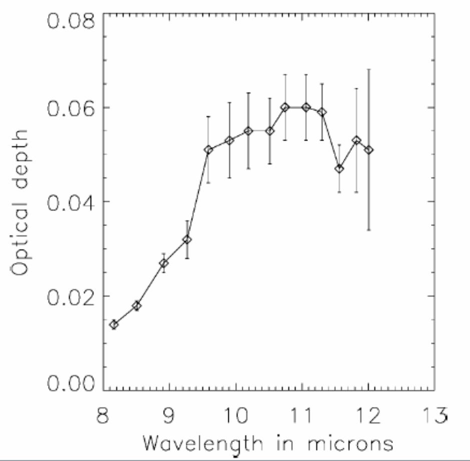
- VLTI/MIDI and KI 8-13 micron observations available since 2003-04, down to a few Jy, B > 85m, R=30 to 300

Dust characterization: O-rich Miras and SRs

(RR Sco: Ohnaka et al. 2005, RS CrB: Mennesson et al. 2005)







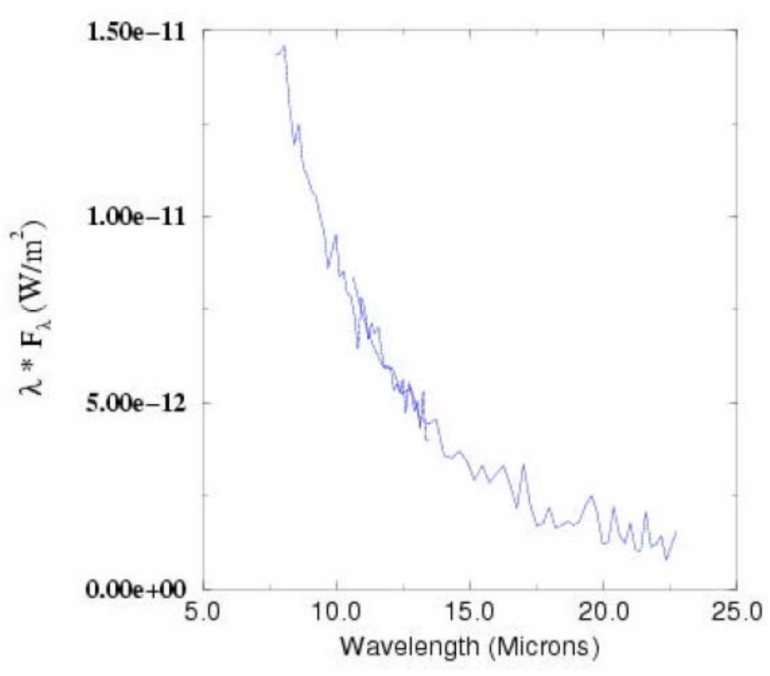
Best fit model for RS CrB KI observations:

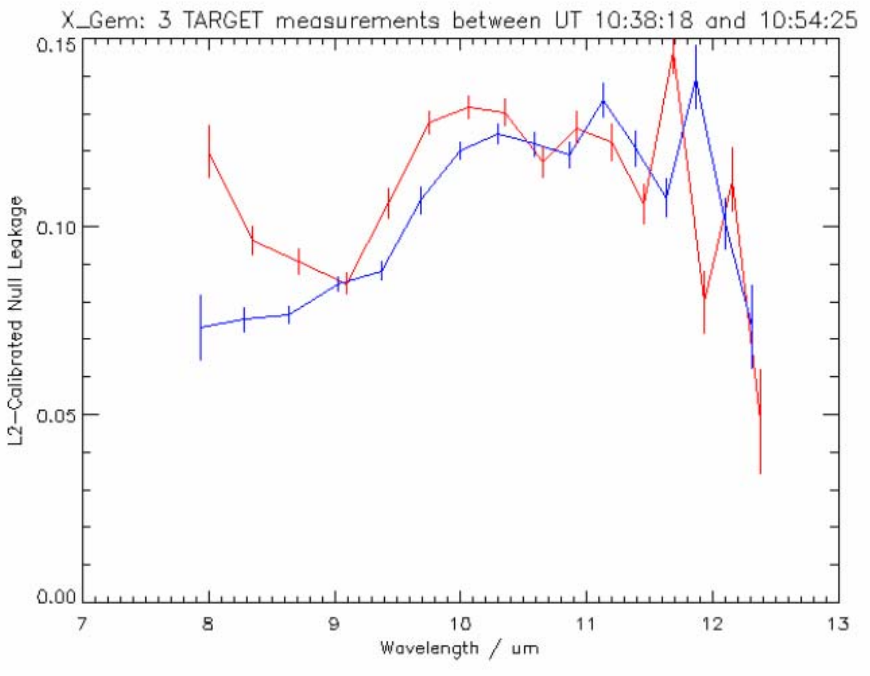
D*=3.78 +/- 0.2 mas, D_{shell}=27.6 +/- 1.2 mas

T_{shell} = 1160 +/- 300 K, $\tau_{11.1\mu m}$ = 0.04 – 0.3

Shell with amorphous silicates and amorphous alumina

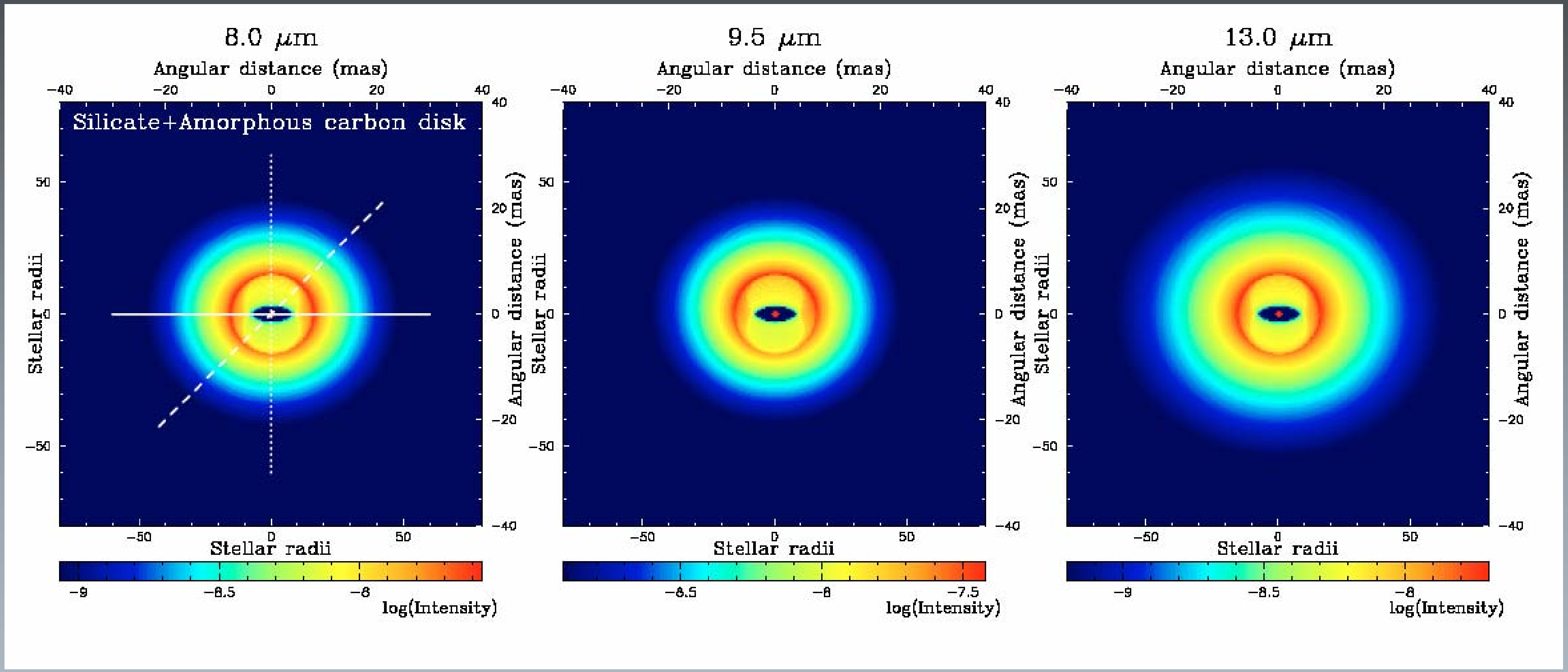
Dust Characterization: Nulling observations of the Mira X Gem (KI 2006)





Also suggests $R_{shell} > 5 R^*$

Dust characterization: the silicate C star Hen 38 (MIDI, Ohnaka et al. 2006)

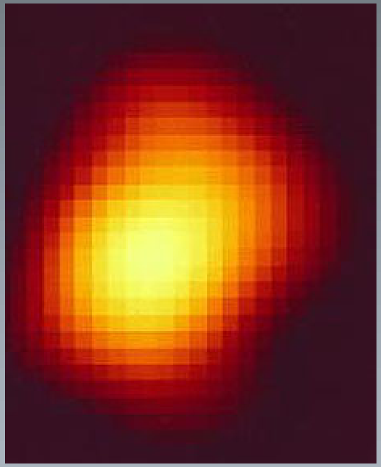


Silicate C stars: circum-binary dust disks rather than circum-companion disks??

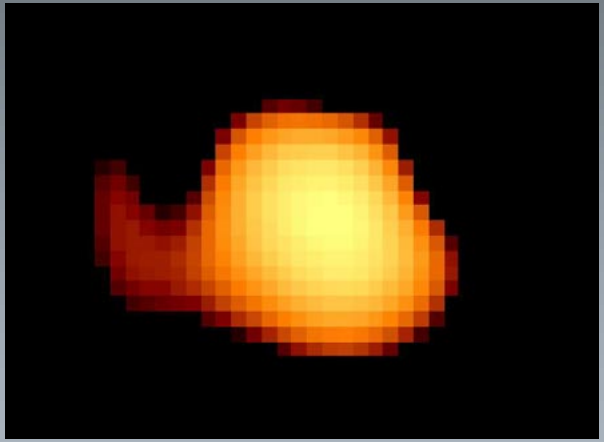
Future of AGB dust characterization by thermal infrared interferometry

- **High spectral resolution with MIDI: R=300, search for features of dust surviving at high temperature (Al_2O_3), separating species with overlapping features at low resolution (e.g. C_2H_2 / HCN, alumino silicate compounds / Mg rich compounds)**
- **Study of correlation between dust composition, location and mass loss rate**
- **High visibility accuracy (<1% → constrast > 200) measurements accessible via nulling with KIN and LBTI**
- **Observe a large stellar sample to decide between individual and generic characteristics**

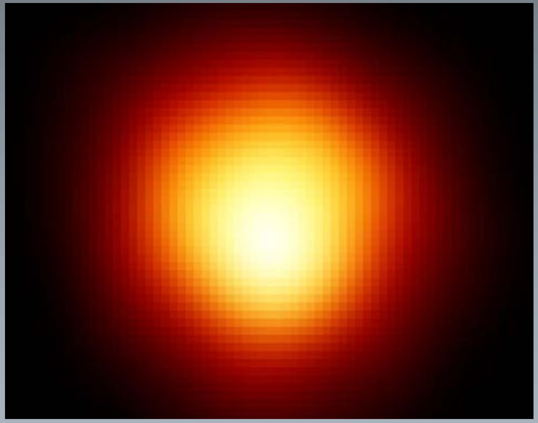
Evidences for asymmetries



Mira HST
visible image



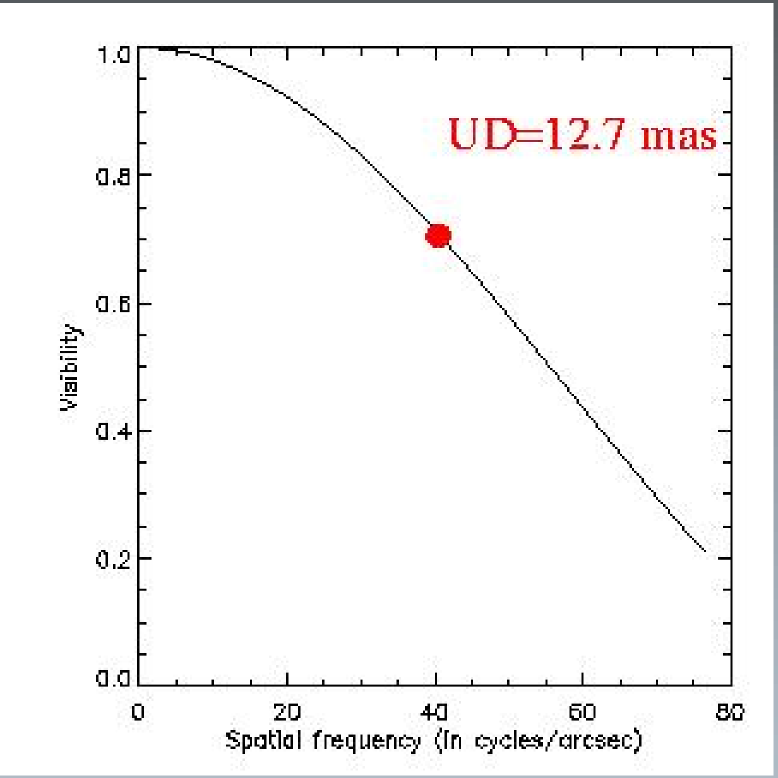
Mira HST UV image



Betelgeuse HST UV
image

The danger of using UDs…

- Unrealistic “size” variations
- One can conclude erroneously to size changes vs time or azimuths:



- Phase closure is a less ambiguous quantity

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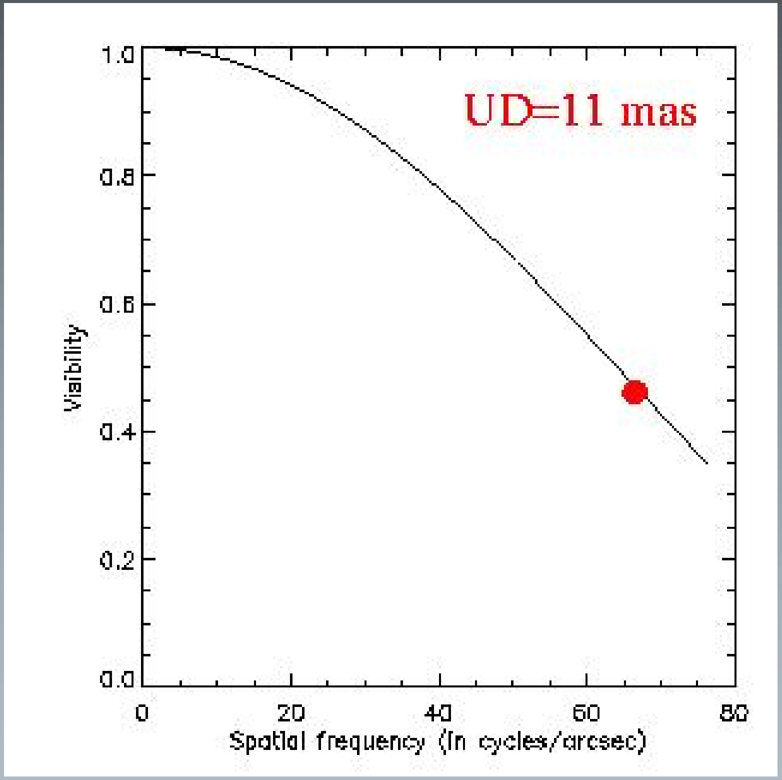

- Phase closure is a less ambiguous quantity

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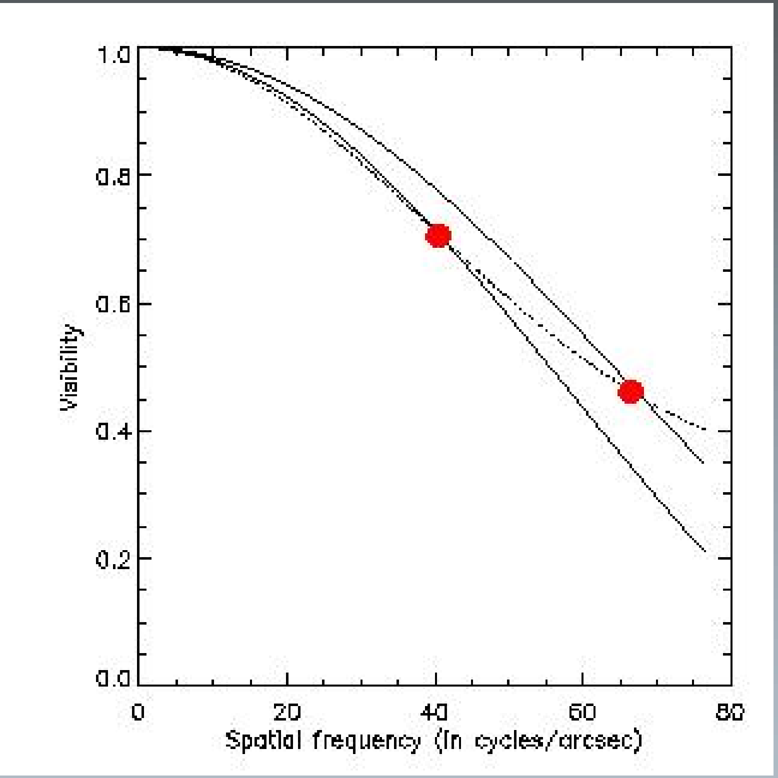
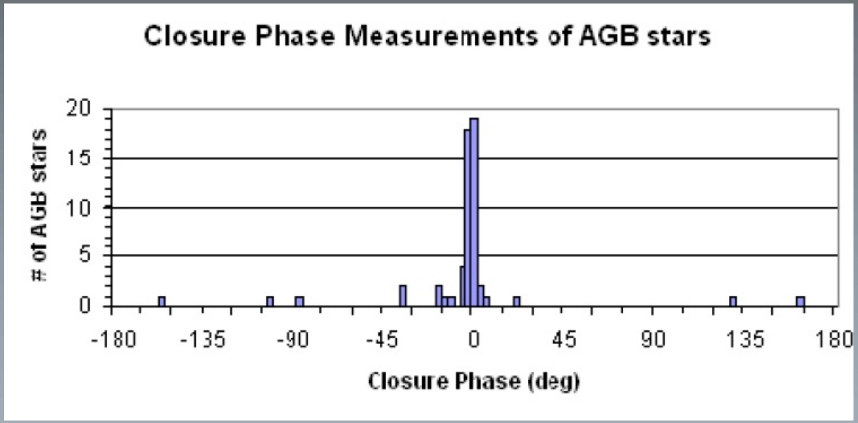


- Phase closure is a less ambiguous quantity

AGB stars phase closure measurements

(IOTA H-band 3 telescope IONIC set-up, Monnier et al. 2004)

- Work by Ragland et al 2006: out of 56 nearby AGB stars 29% show asymmetries



- Restricting to well resolved stars: 75%, and 100% of O-rich
- Hyp: all Mira stars will show some asymmetry when observed at sufficient angular resolution

Future developments and needs

- **Lots of new facilities coming on line with:**
  - **Higher spectral resolution: MIDI (R=300) AMBER (R=10000)**
  - **Multi-aperture phase closure, differential phase and imaging (e.g. CHARA)**
  - **High dynamic range: nulling (KI and LBTI)**
  - **Astrometry (PRIMA)**

- **Transition of skills towards more astrophysics and finer models is needed (incorp. radiative transfer through dust + complete molecular treatment + dynamics)**

- **Crucial need for more collaboration and coordination of simultaneous observations at different wavelengths (e.g. RS Oph)**

IOTA – PTI – Keck interferometric observations of the recurrent nova RS Oph

H/K band observations:

No expansion!

(Monnier et al. 2006)

Model Parameter	2006 Feb 16 – 23 (Days 4 – 11)	2006 Feb 26 – Mar 13 (Days 14 – 29)	2006 Apr 02 - 18 (Days 49 – 65)
Gaussian Profile (fitting only to 1.65μm)			
FWHM (milliarcseconds)	3.30 ± 0.09	3.47 ± 0.03	2.87 ± 0.07
Reduced χ^2 (V^2)	0.6	1.3	1.1
Reduced χ^2 (CP)	1.3	3.6	5.4
Gaussian Profile (fitting only to 2.2μm)			
FWHM (milliarcseconds)	2.56 ± 0.24	N/A	2.00 ± 0.09
Reduced χ^2 (V^2)	0[a]	N/A	1.0
Reduced χ^2 (CP)	N/A	N/A	N/A
Binary Model[b] (fitting to 1.65μm & 2.2μm data)			
Separation (milliarcseconds)	3.13±0.12	3.23±0.13	3.48±0.23
Position Angle[c] (degs E of N)	36±10[d]	45±5	27±5
Brightness Ratio[c]	0.42±0.06	0.40±0.06	0.21±0.03
Reduced χ^2 (V^2)	0.6	1.7	1.2
Reduced χ^2 (CP)	1.1	1.3	0.5

N band observations:

7mas structure