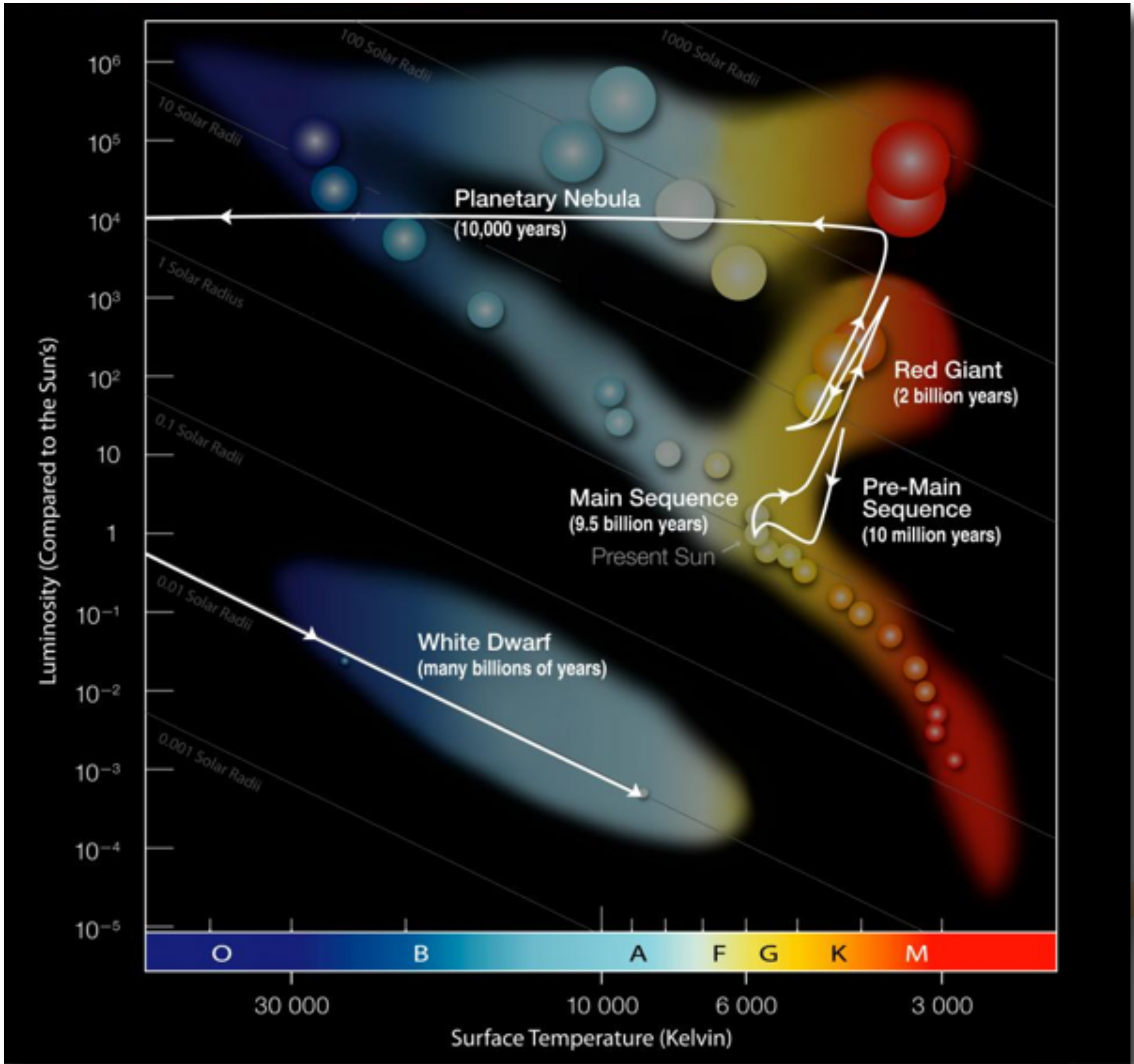
Interferometry* of evolved stars

Tijl Verhoelst
Instituut voor Sterrenkunde, KULeuven, B

* Only optical/IR long-baseline interferometry, no lunar occultations, aperture masking, or radio interferometry

Stellar Evolution after the Main Sequence

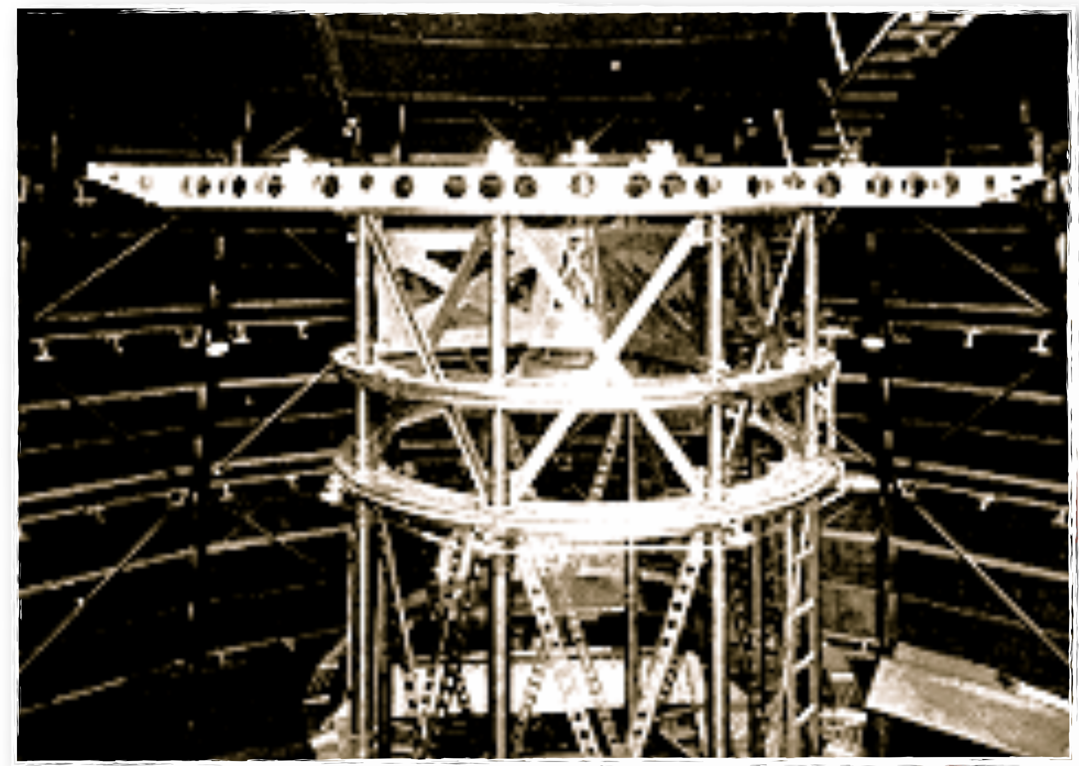


Topics for interferometry

- *Stellar diameters*
  - linear radii
  - T_{eff} calibrations
- *Limb darkening*
- *Surface spots*
- *λ-dependent diameters*
- *Time-dependent diameters*
- *Circumstellar material*
  - outflows
  - dense torii
  - stable Keplerian disks

Stellar diameters: the early days

Albert Michelson



The 20 foot interferometer on Mt. Wilson

Diameters of 7 red (super)giants:

Betelgeuse, Arcturus, Antares, Aldebaran, α Herculis, β Pegasi, and Mira

Michelson & Pease 1921, ApJ v53, p249

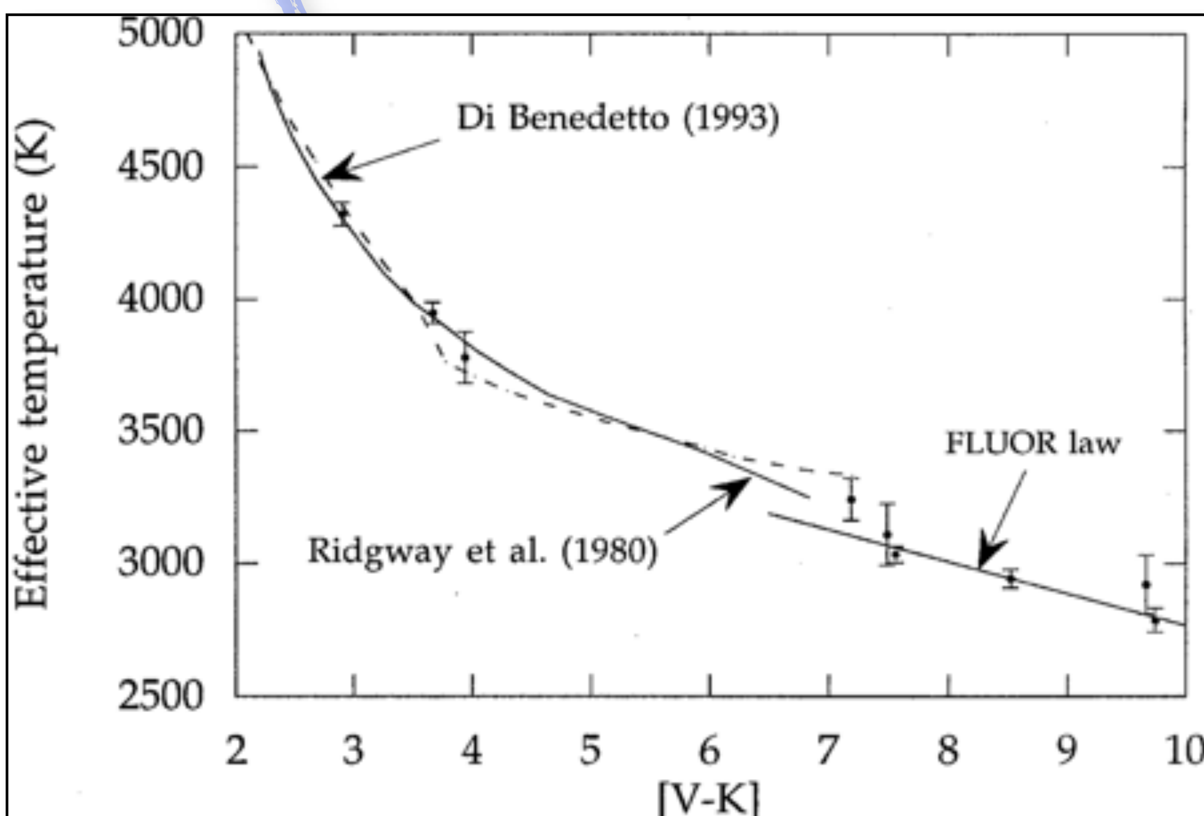
Effective temperatures

$$L = 4\pi R^2 \sigma T_{eff}^4$$

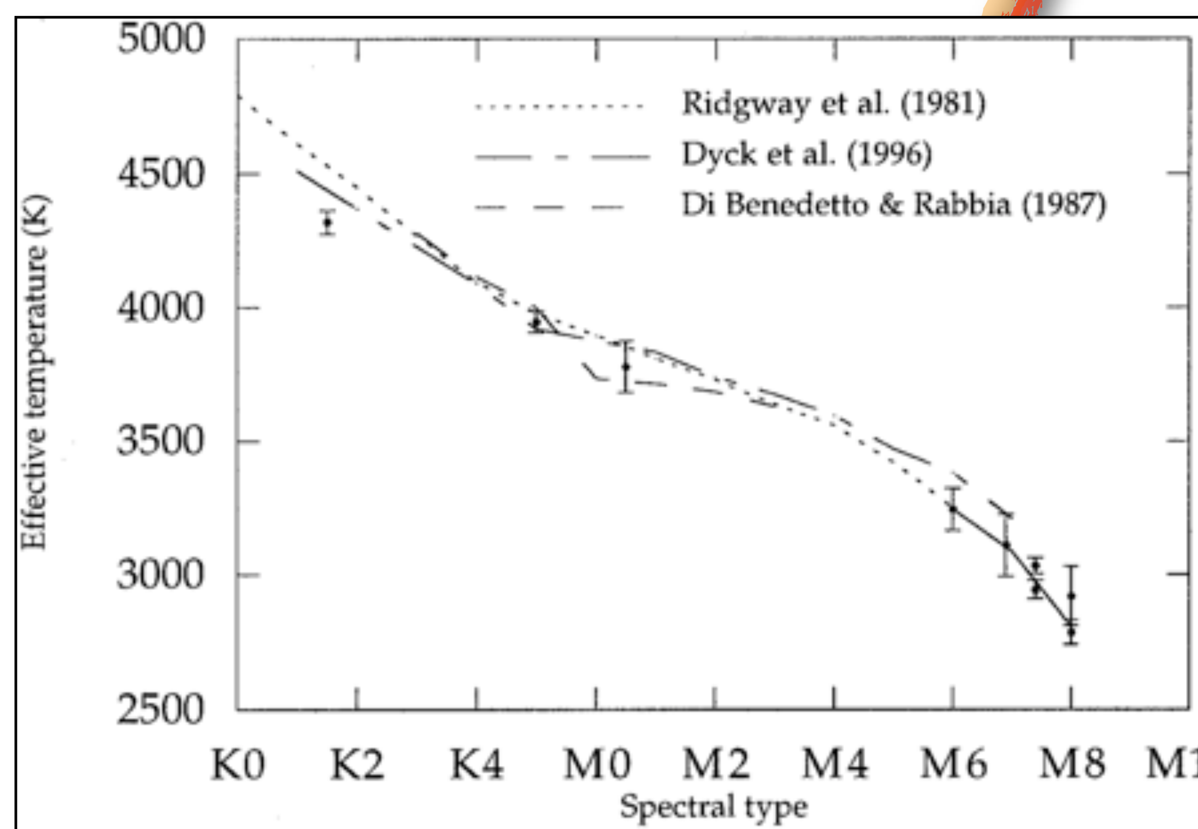
↓

$$T_{eff} = 7400 \left(\frac{F_{bol}}{10^{-13}\,Wcm^{-2}}\right)^{1/4} \left(\frac{1\,mas}{\oslash_{LD}}\right)^{1/2} K$$

- Di Benedetto & Rabia (1987): I2T
- Di Benedetto (1993): I2T, Mark III
- Dyck et al. (1996): IOTA
- Perrin et al. (1998): IOTA (FLUOR)
- Dyck et al. (1998): IOTA
- Van Belle et al. (1999,2009): PTI
- Baines et al. (2010)



Perrin et al. (1998)



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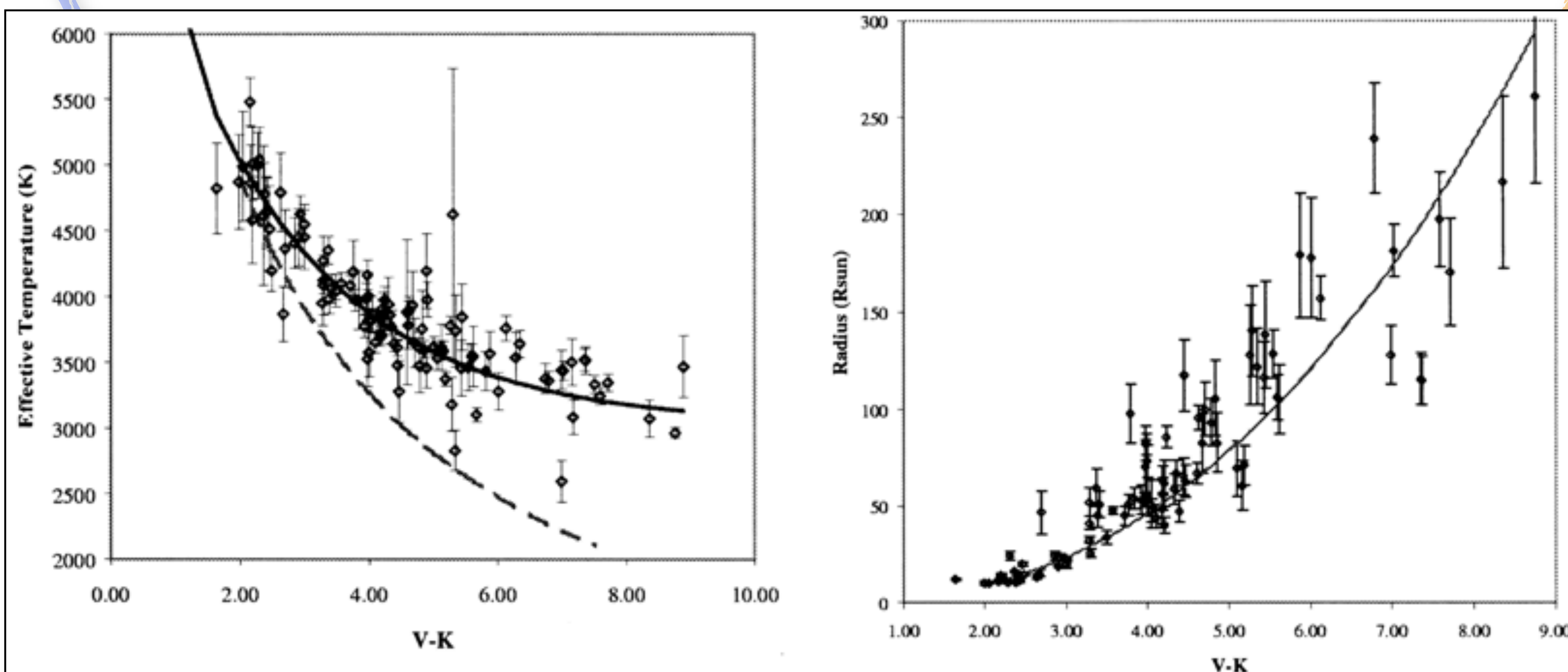
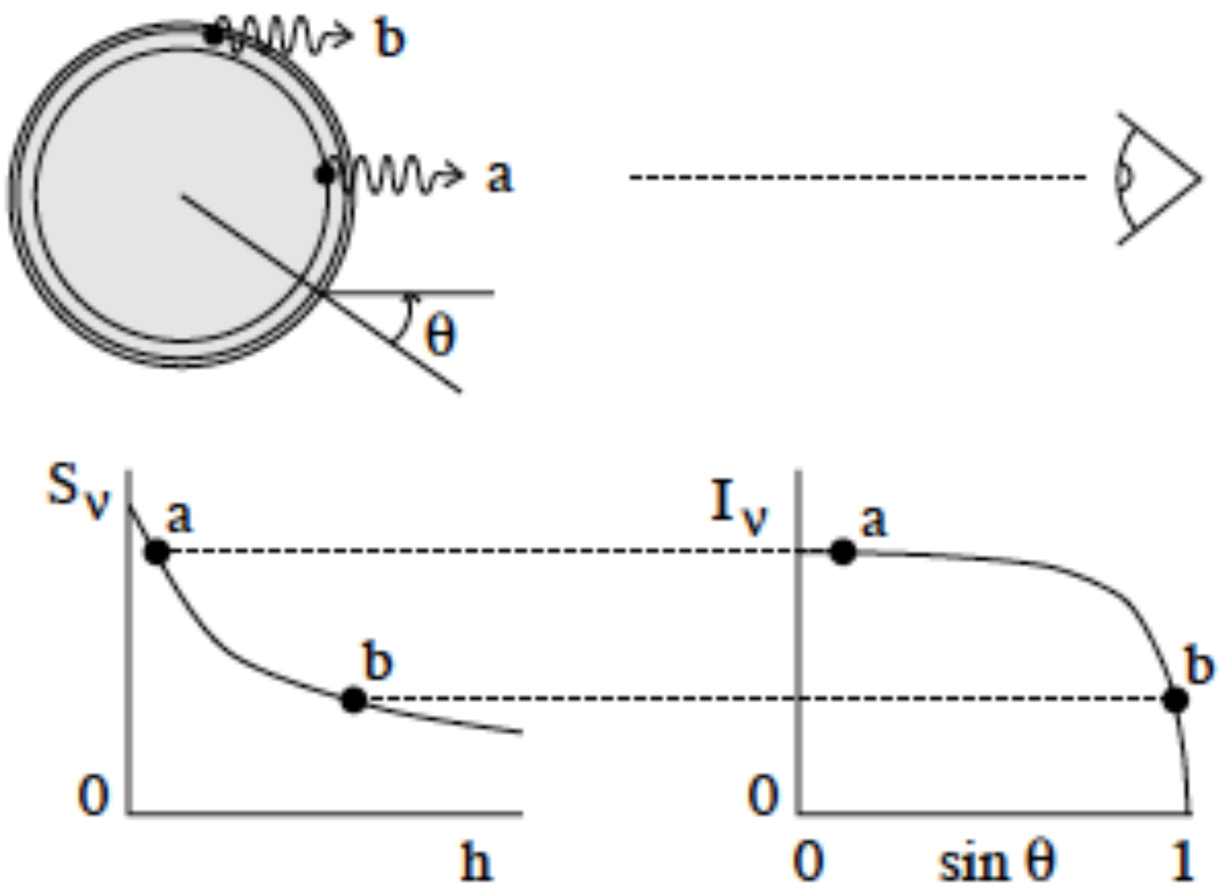


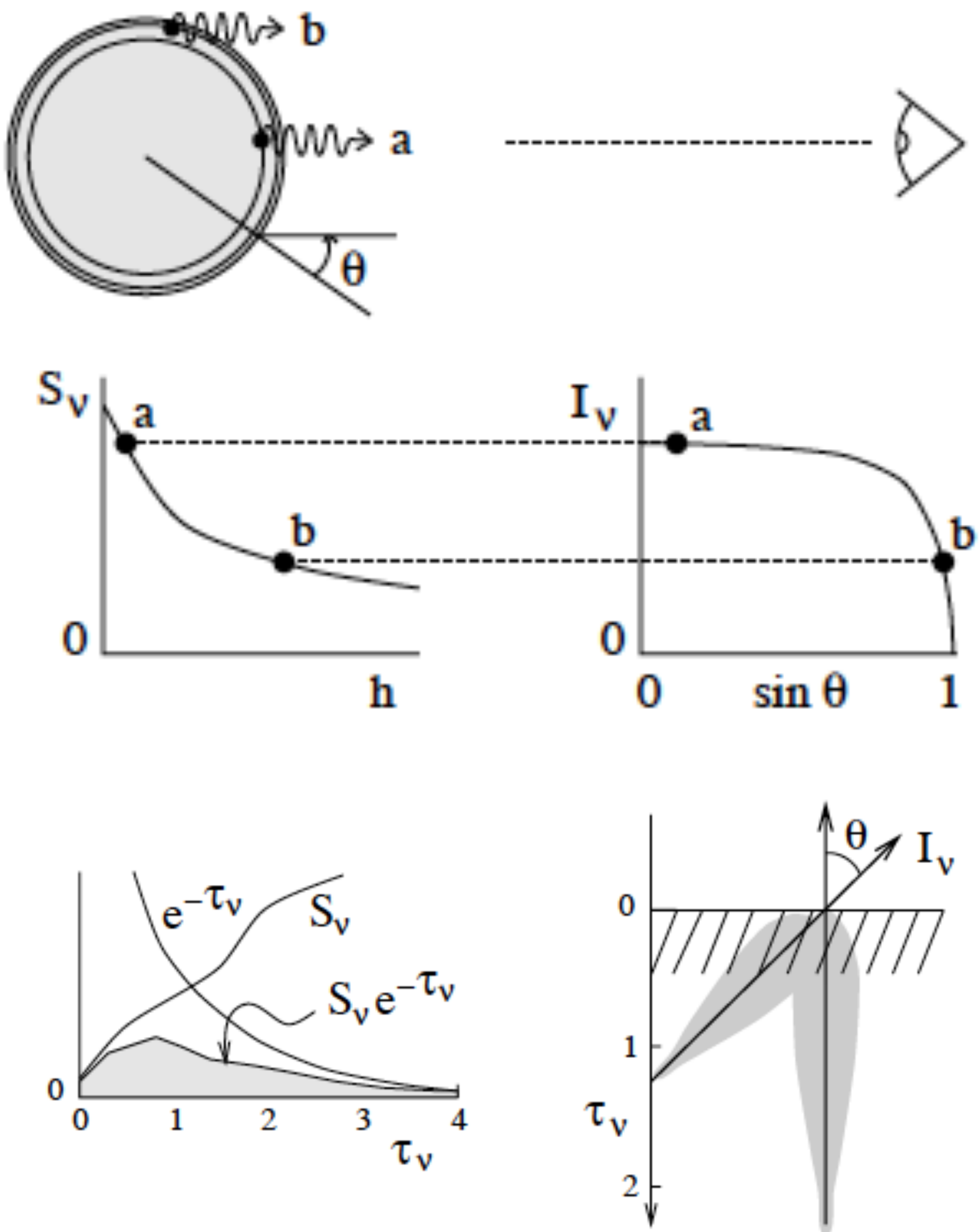
Van Belle et al. (2009)

Limb darkening: studying the photospheric structure



From course notes by Rob Rutten

Limb darkening: studying the photospheric structure



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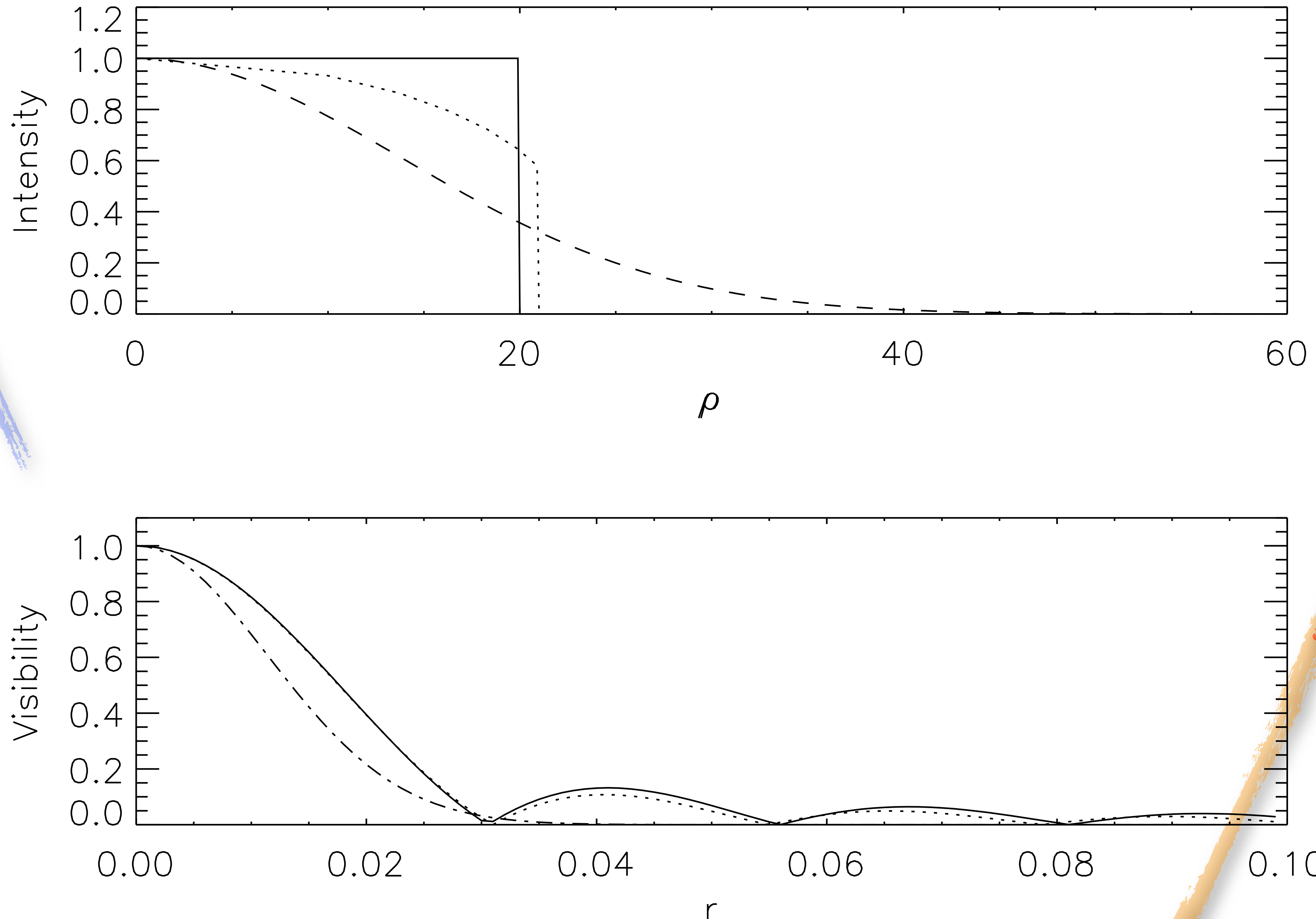
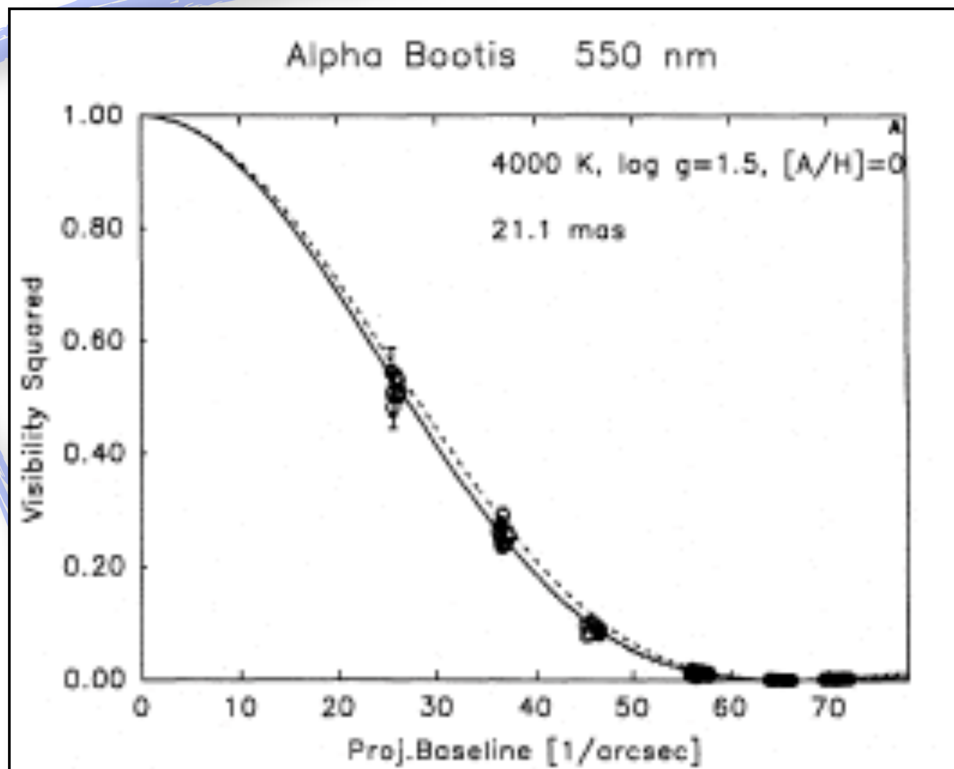
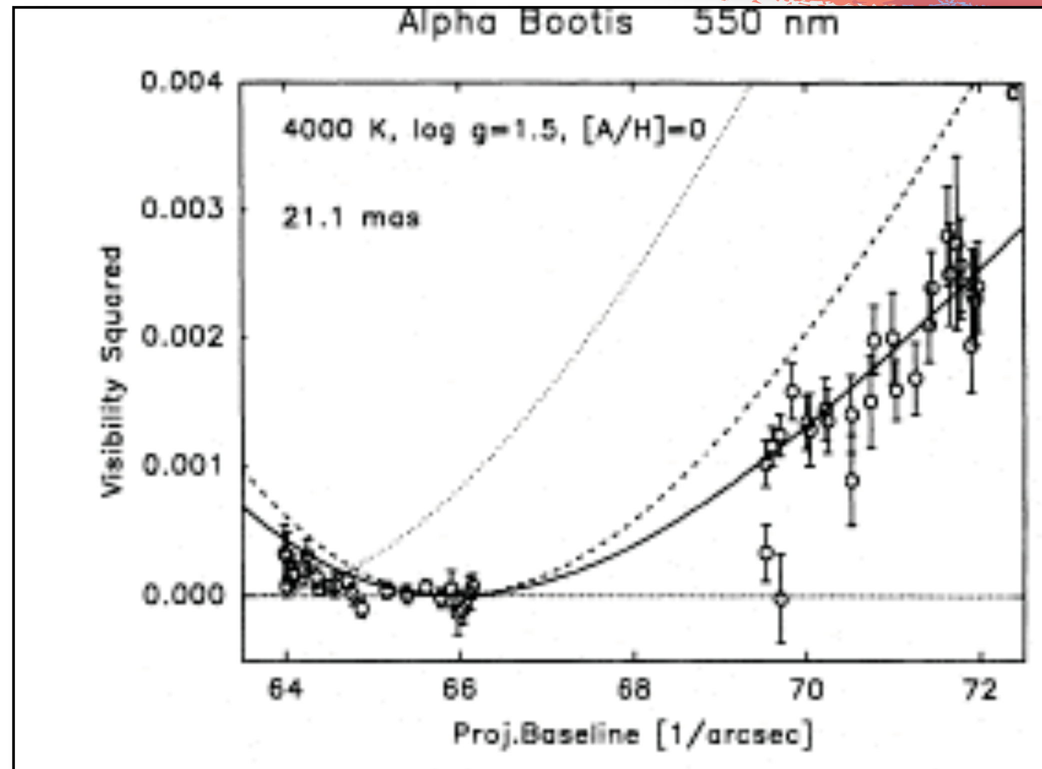
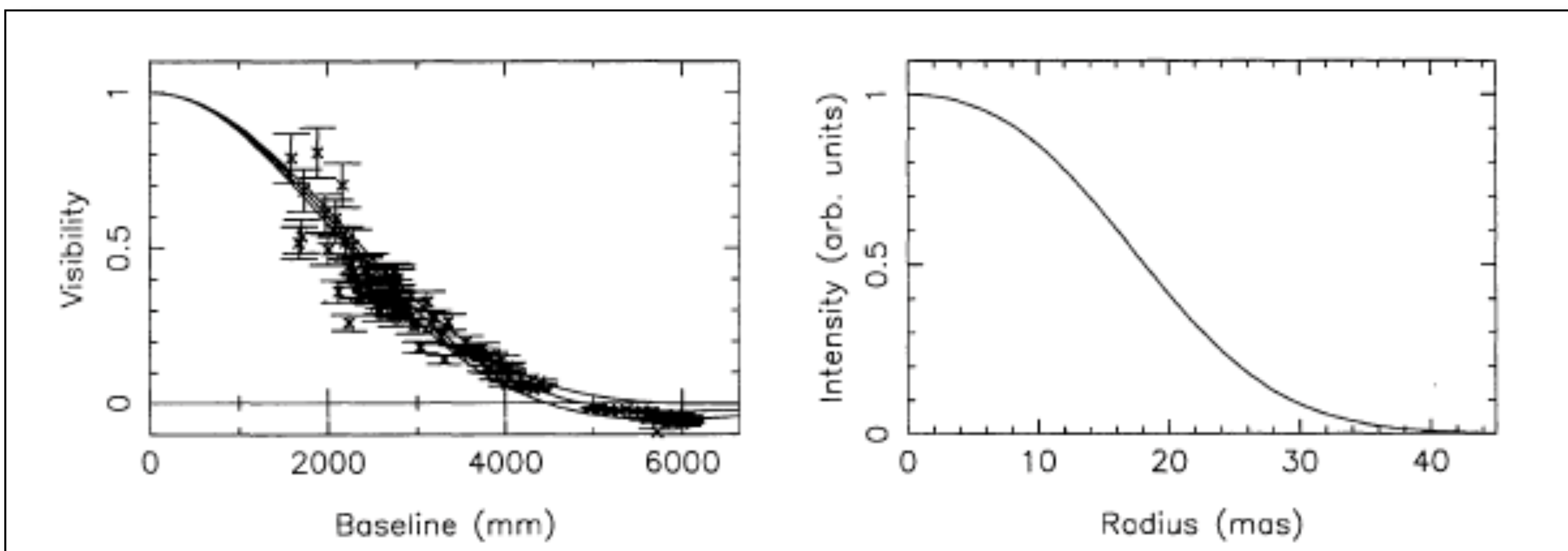


Limb darkening: studying the photospheric structure



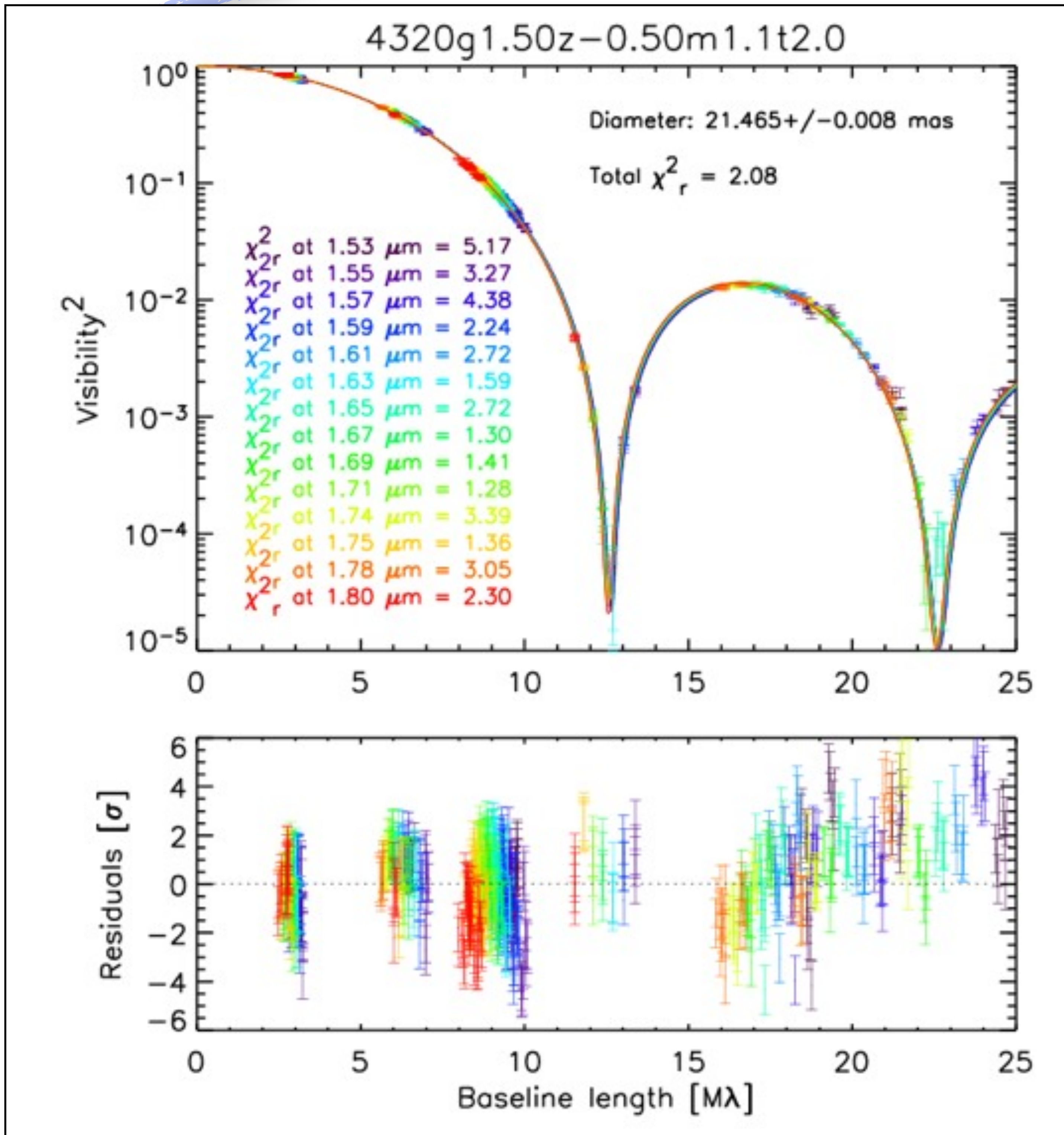


Quirrenbach et al. (1996), MkIII observations of Arcturus

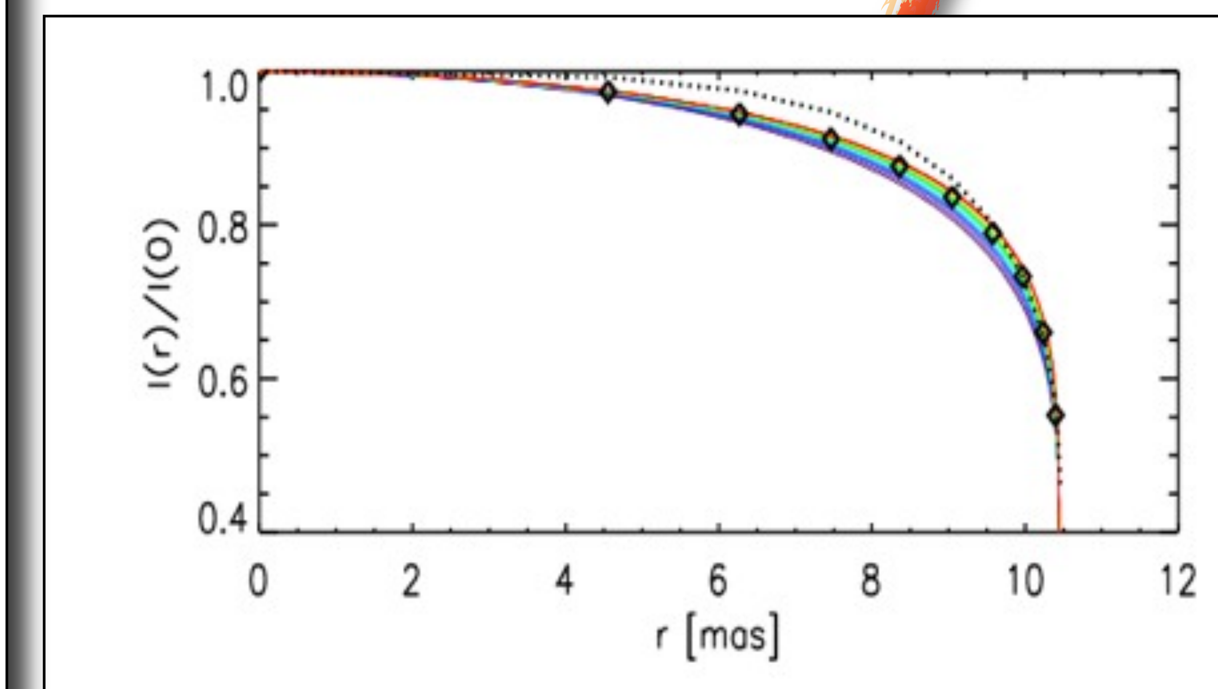


Burns et al. (1997), COAST observations of Betelgeuse

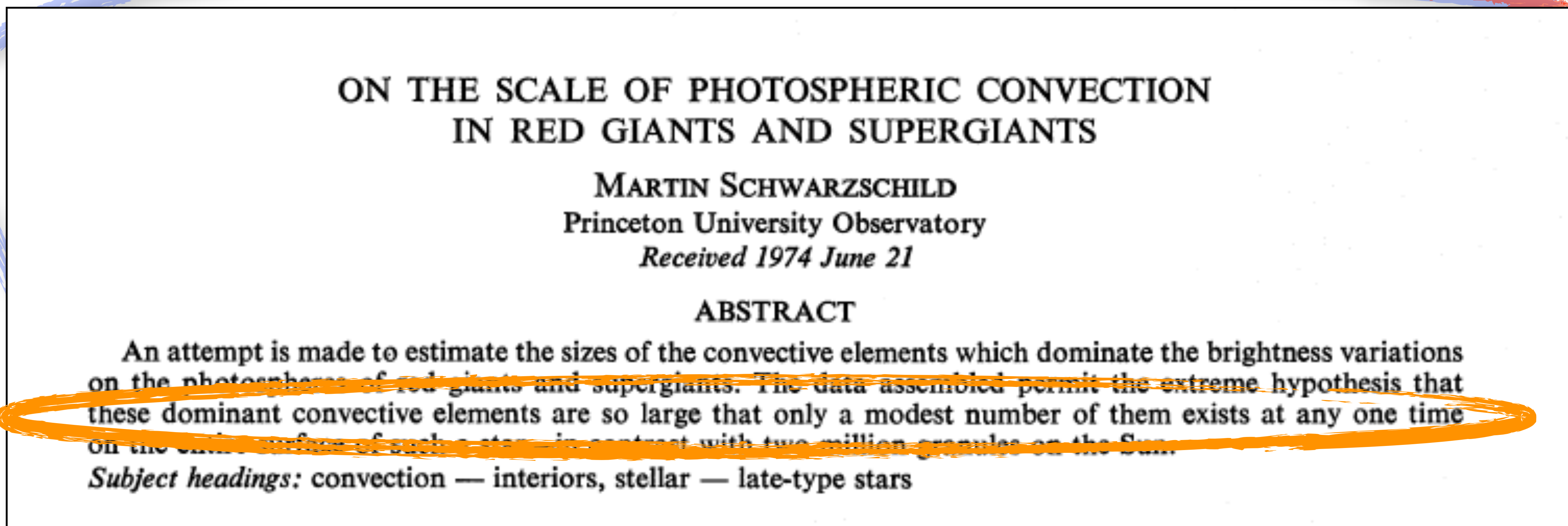
Limb darkening: studying the photospheric structure



Lacour et al. (2008): IOTA/IONIC observations of Arcturus, amounting to 924 visibility measurements and 308 closure phases



Surface spots as consequence of convection



ON THE SCALE OF PHOTOSPHERIC CONVECTION IN RED GIANTS AND SUPERGIANTS

MARTIN SCHWARZSCHILD
Princeton University Observatory
Received 1974 June 21

ABSTRACT

An attempt is made to estimate the sizes of the convective elements which dominate the brightness variations on the photospheres of red giants and supergiants. The data assembled permit the extreme hypothesis that these dominant convective elements are so large that only a modest number of them exists at any one time on the entire surface of such a star—in contrast with two million granules on the Sun.

Subject headings: convection — interiors, stellar — late-type stars

- Schwarzschild (1975)
- Freytag et al. (2002): "Spots on the surface of Betelgeuse -- Results from new 3D stellar convection models"
- Freytag & Höfner (2008): "Three-dimensional simulations of the atmosphere of an AGB star"

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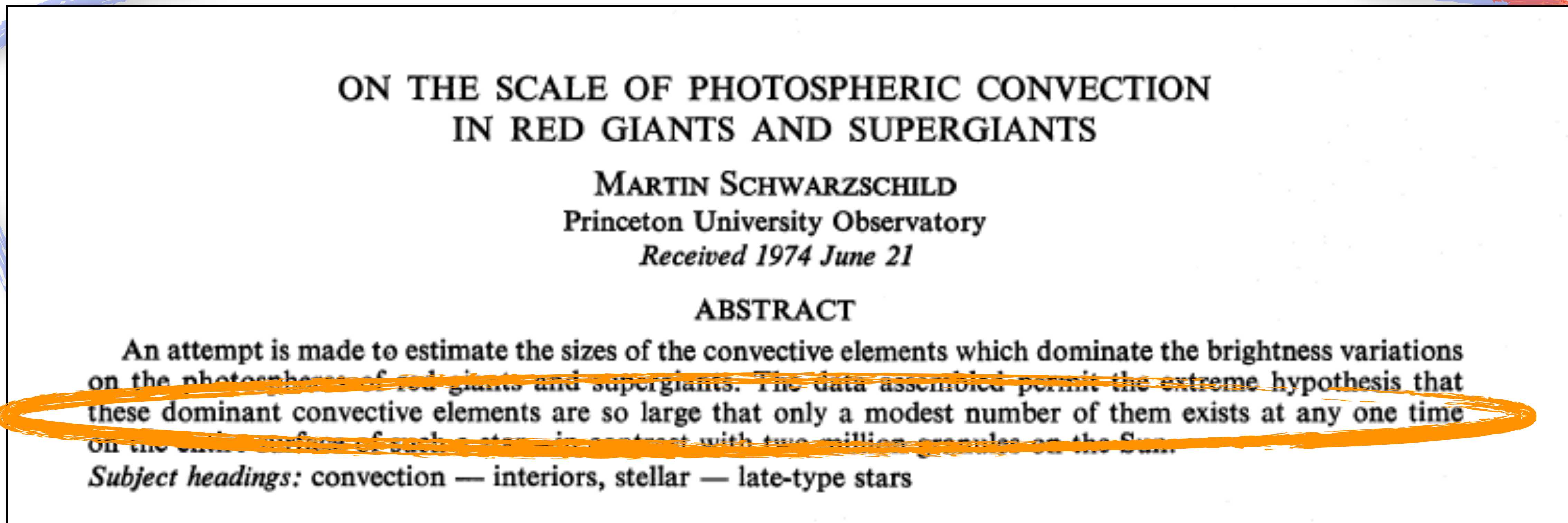

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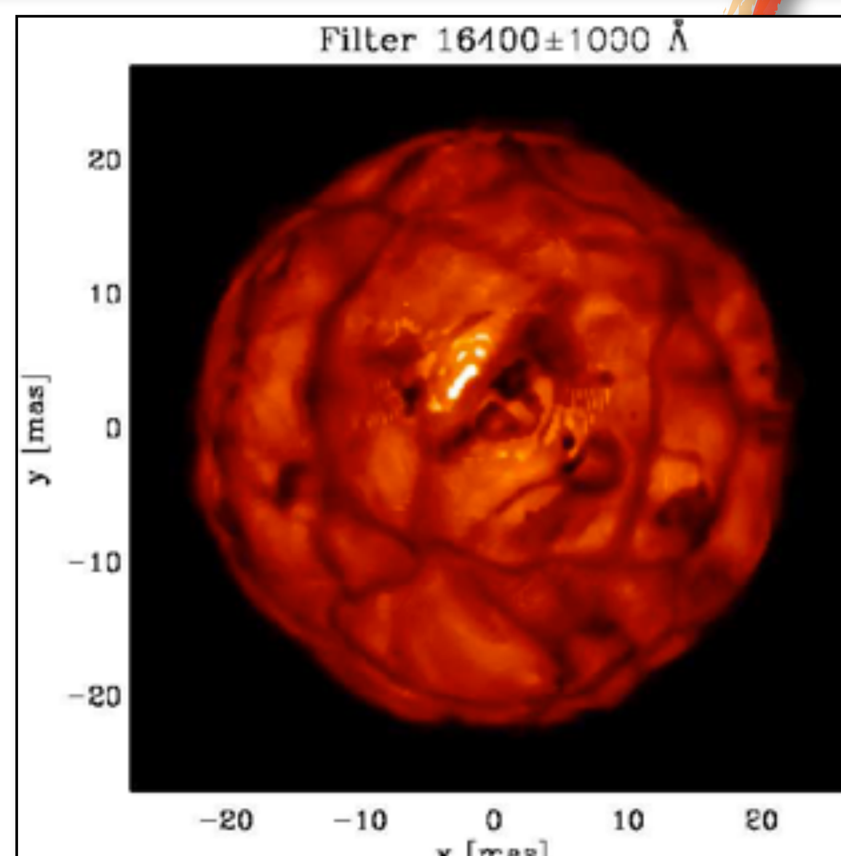

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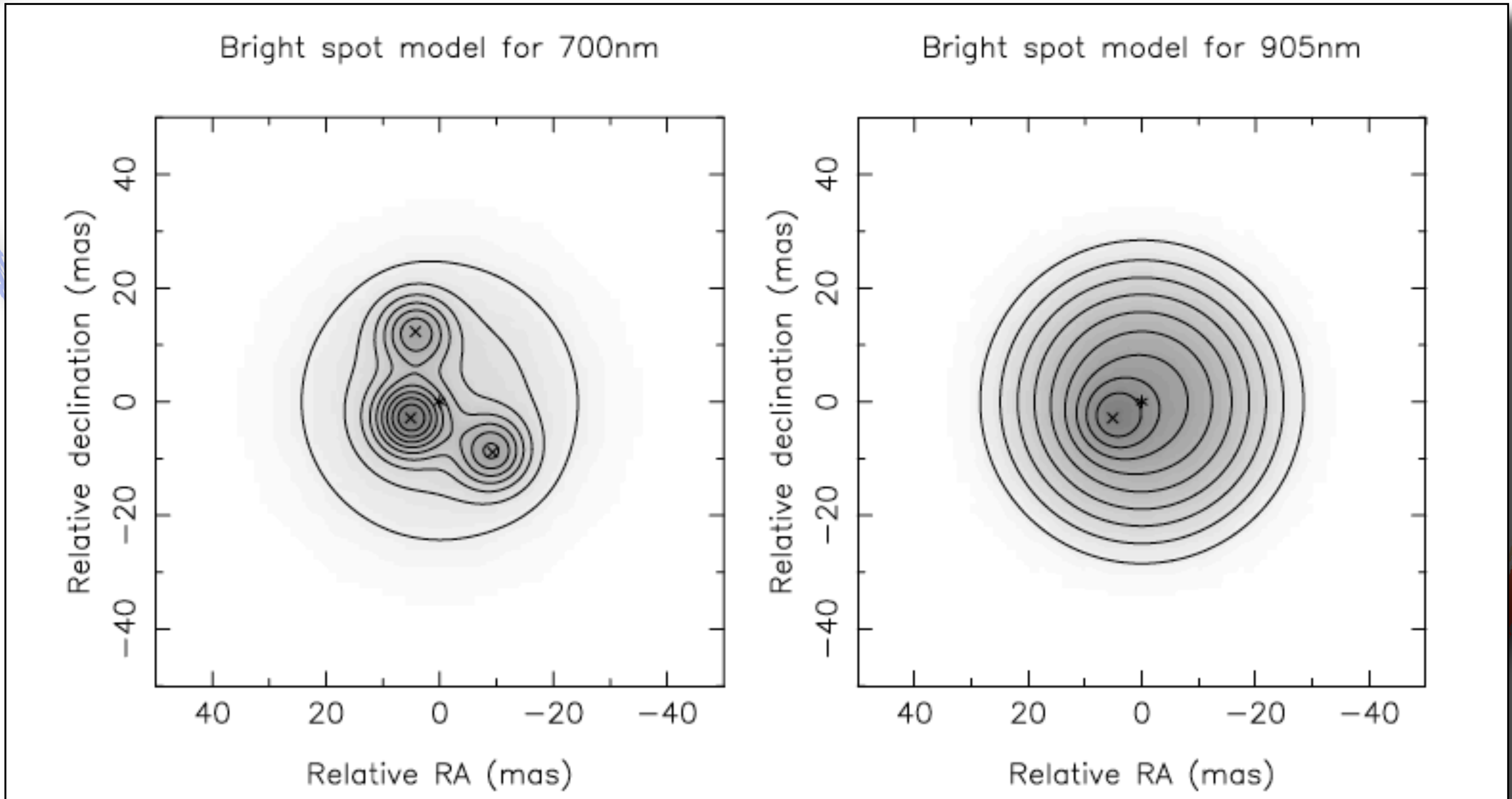
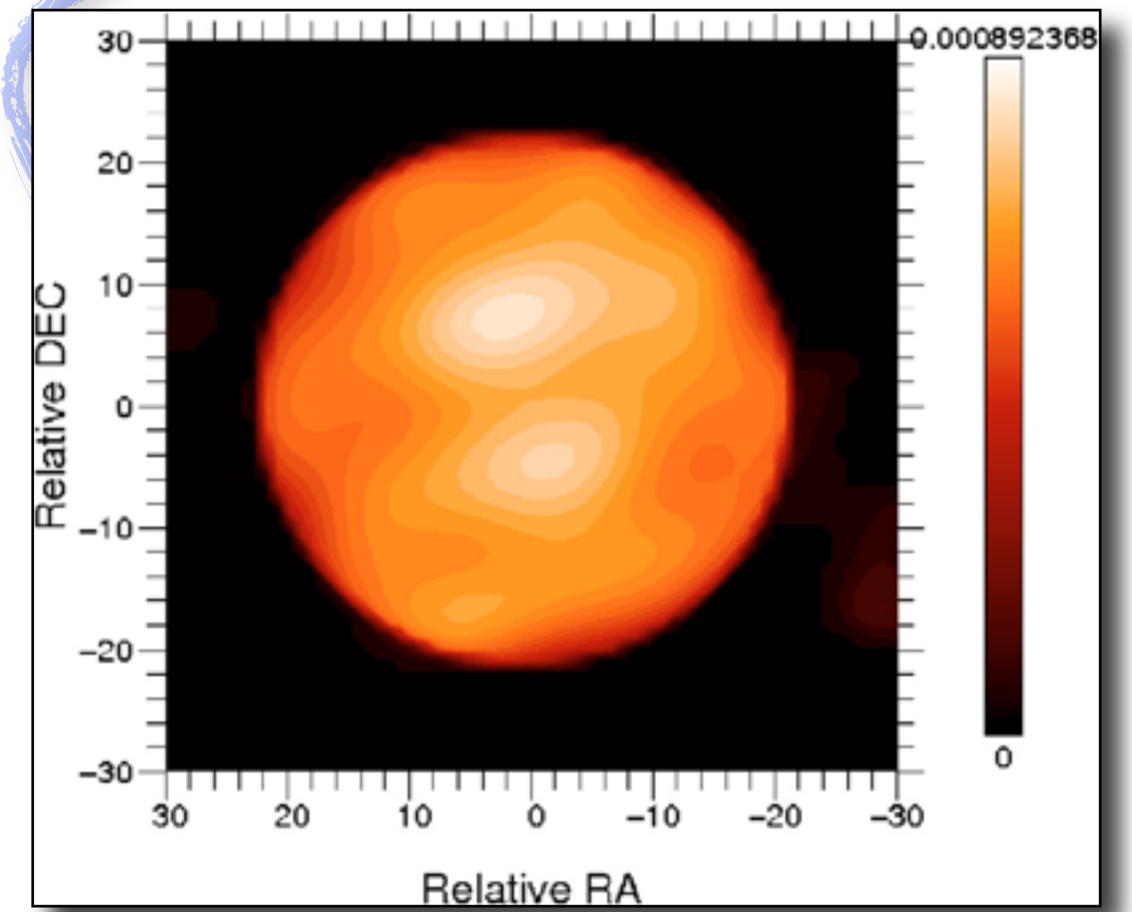
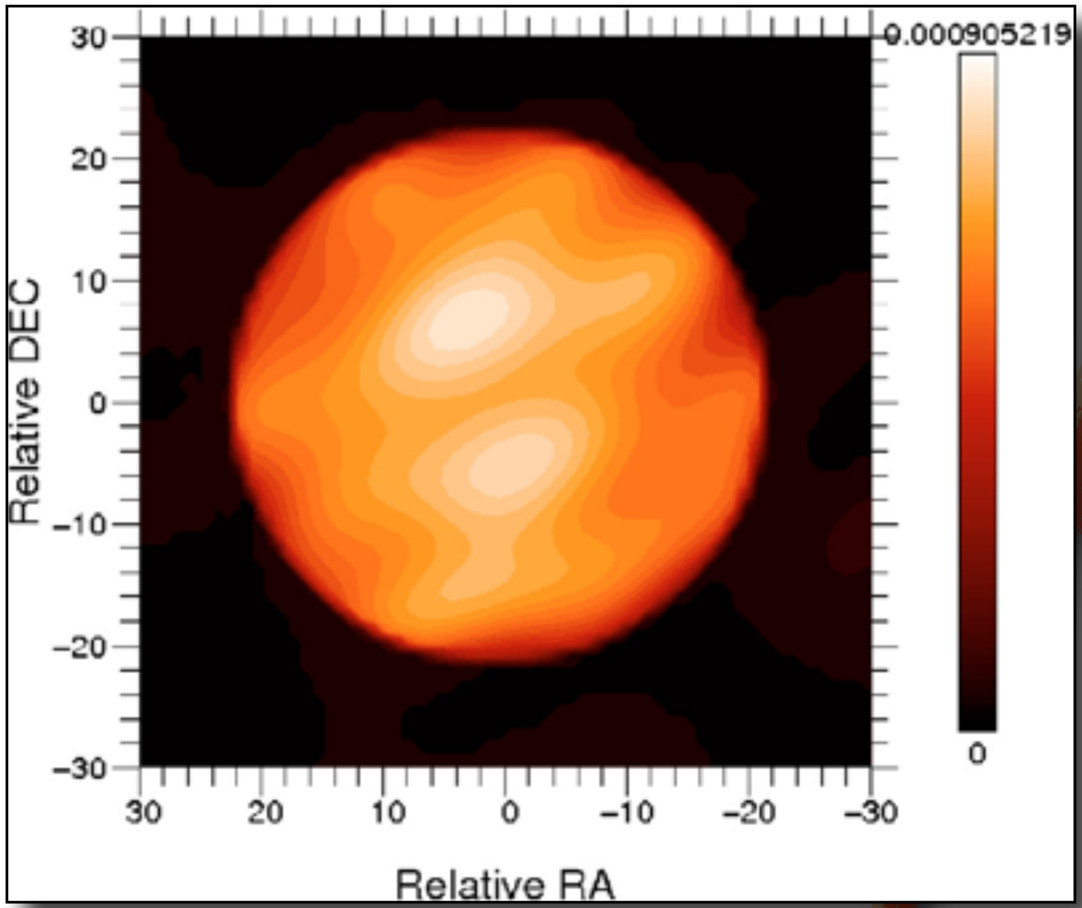


Young et al. (2000): WHT and COAST observations of Betelgeuse

Surface spots as consequence of convection



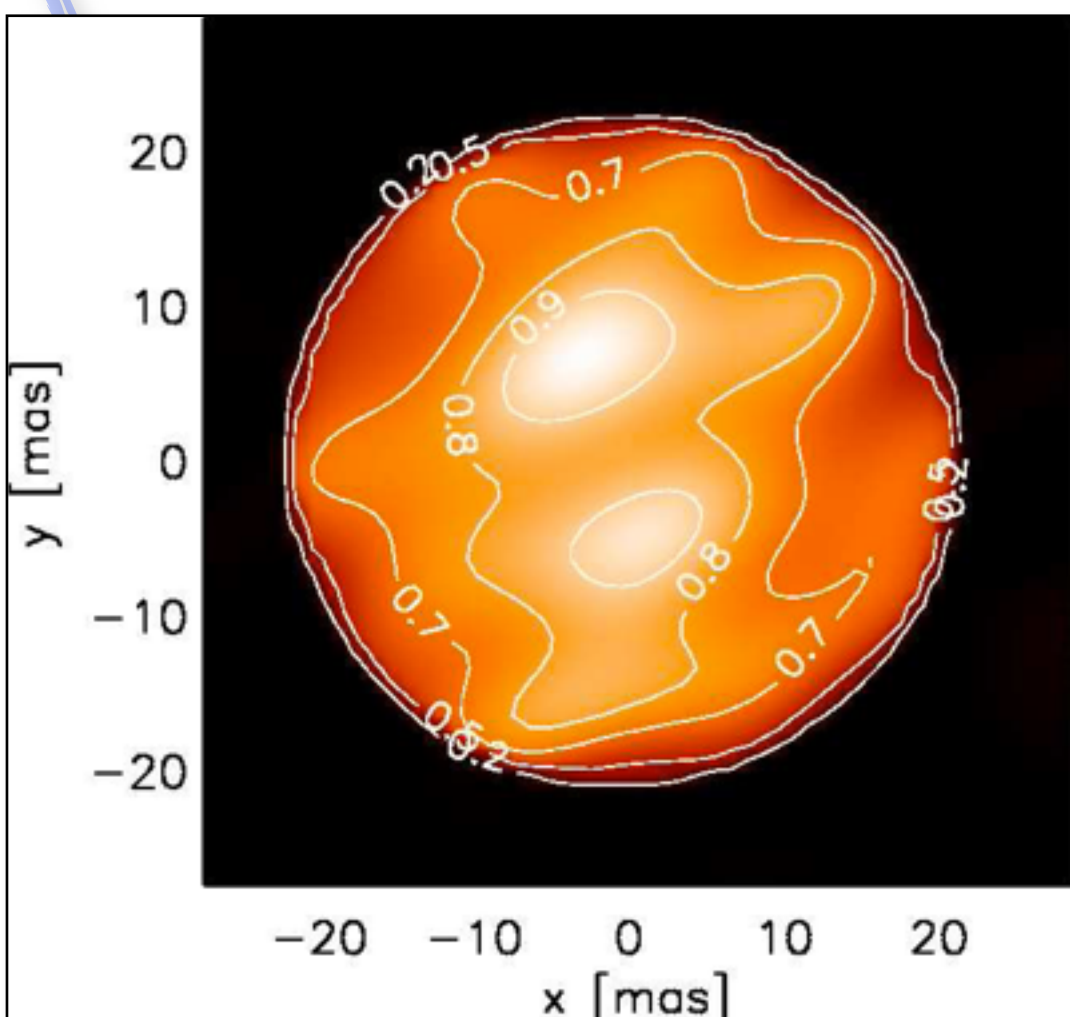


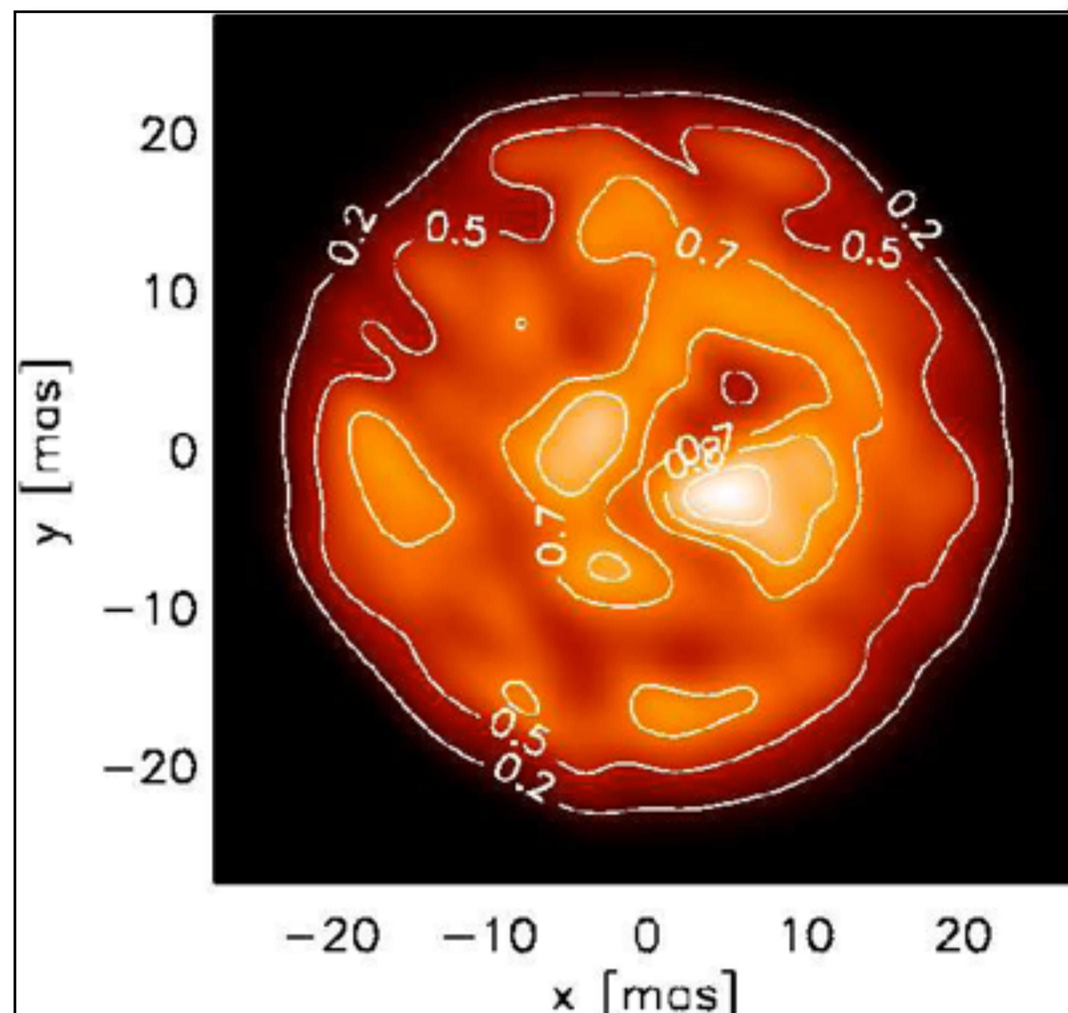
Haubois et al. (2009):
IONIC/IOTA observations of Betelgeuse, image reconstruction with MIRA and WISARD

Surface spots as consequence of convection

Radiative hydrodynamics simulations of red supergiant stars: II. simulations of convection on Betelgeuse match interferometric observations

A. Chiavassa[1,2], X. Haubois[3], J. S. Young[4], B. Plez[2], E. Josselin[2], G. Perrin[3], and B. Freytag[5,6]



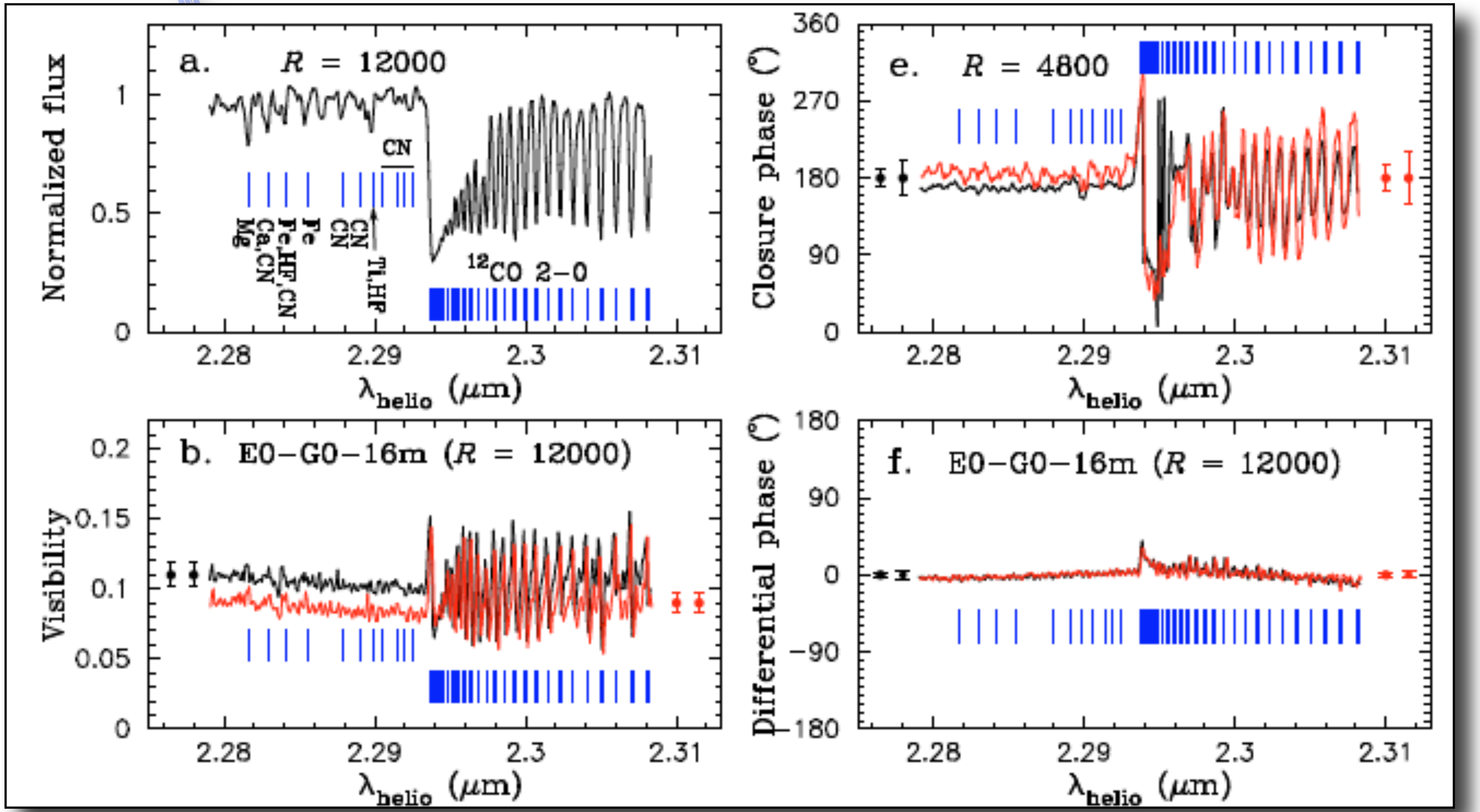


2010, A&A in press

Surface spots as consequence of convection

Ohnaka et al. (2009):

Spatially resolved macroturbulence



A&A 503, 183–195 (2009)

Surface spots as consequence of convection

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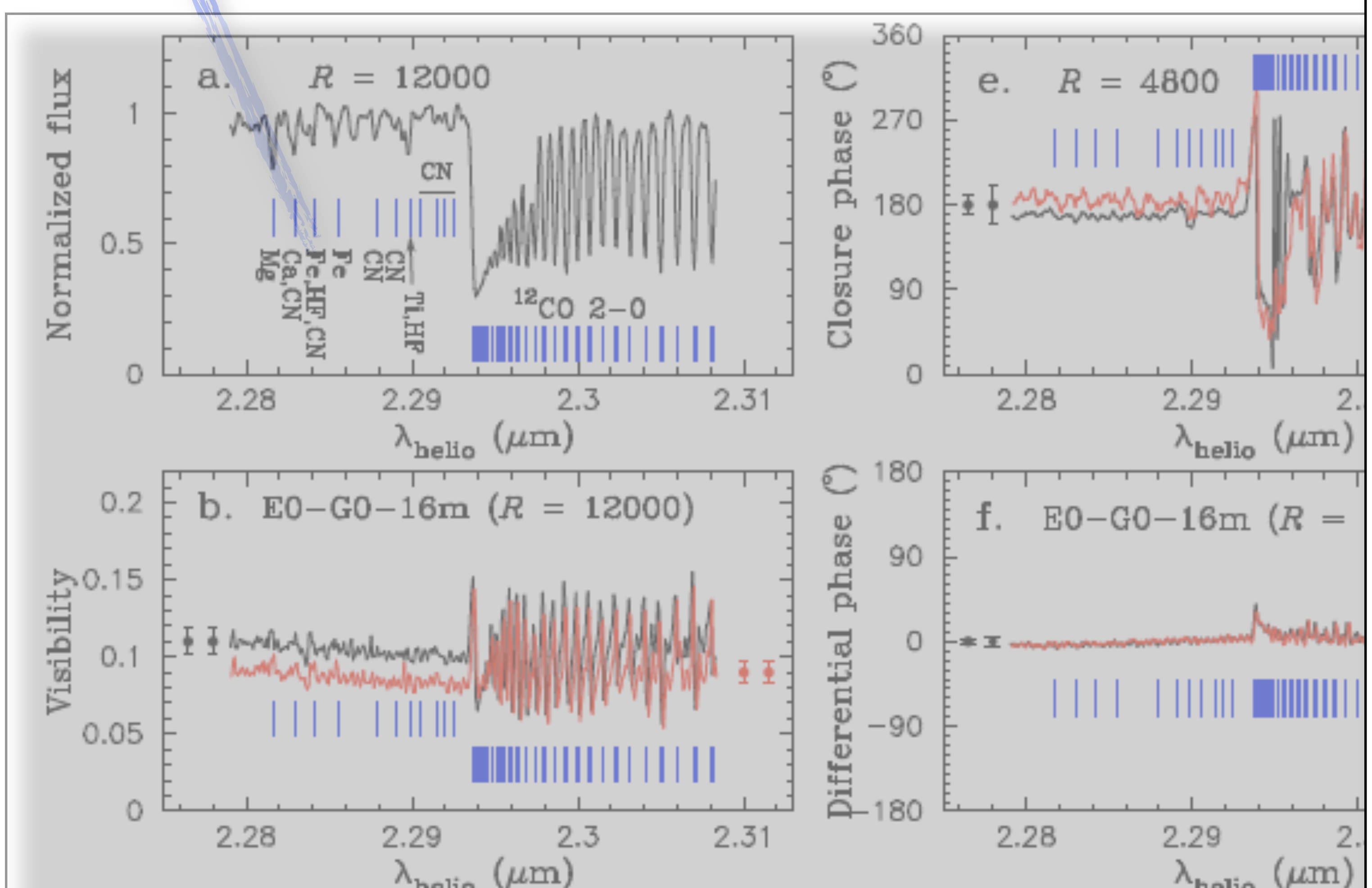
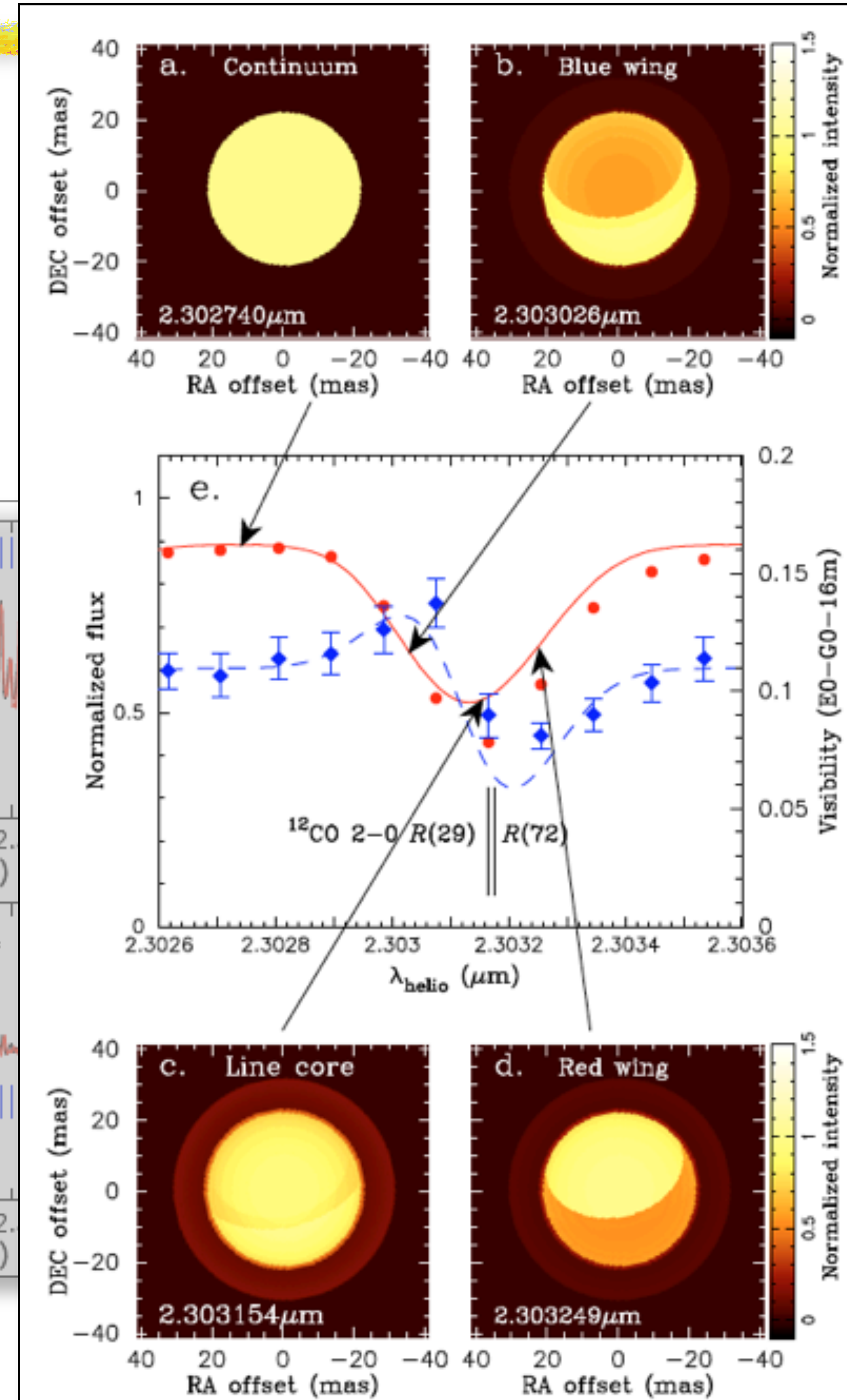




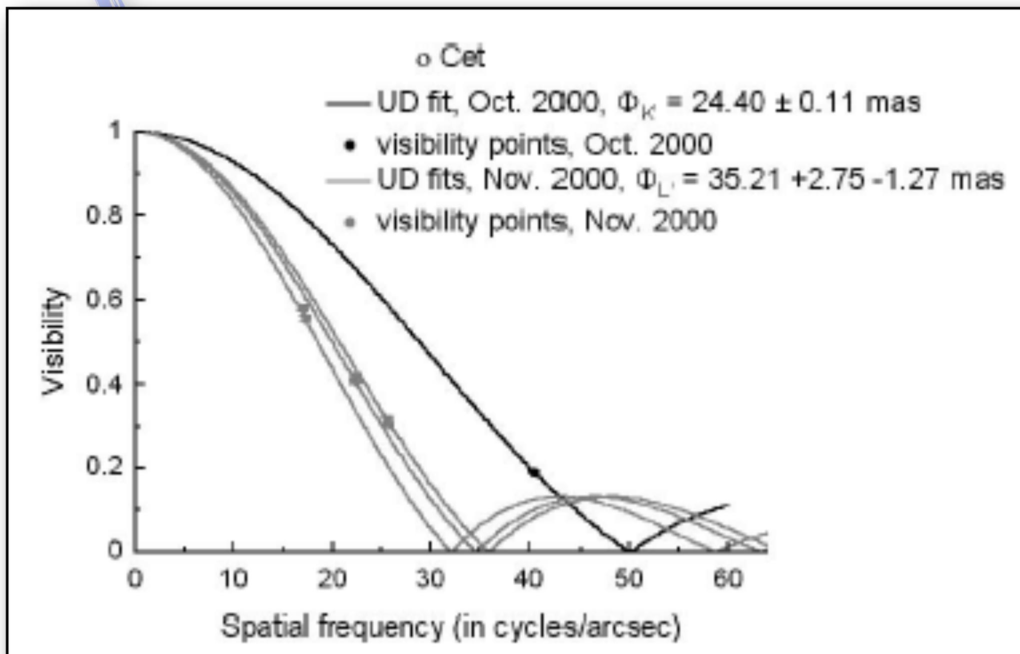
A&A 503, 183–195 (2009)

Wavelength-dependent diameters

EVIDENCE FOR VERY EXTENDED GASEOUS LAYERS AROUND O-RICH MIRA VARIABLES AND M GIANTS

B. Mennesson,[1] G. Perrin,[2] G. Chagnon,[2] V. Coude du Foresto,[2] S. Ridgway,[3] A. Merand,[2] P. Salome,[2] P. Borde,[2] W. Cotton,[4] S. Morel,[5] P. Kervella,[5] W. Traub,[6] and M. Lacasse[6]

Received 2002 March 15; accepted 2002 July 3



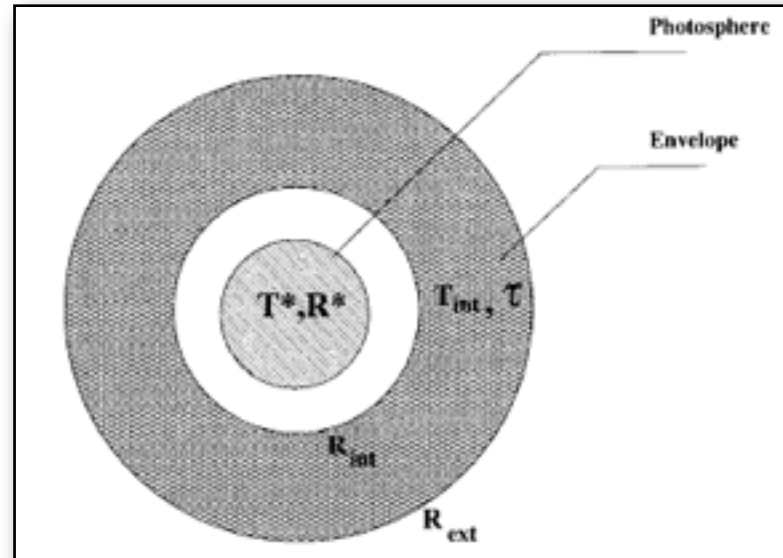


Fig. 3.—Adopted spherically symmetric model. It consists of a central photosphere with radius R^* and effective temperature T^*, surrounded by an envelope with inner radius R_{int}, outer radius R_{ext}, inner temperature T_{int}, and optical depth τ, common to both K' and L' bands.

Molecular slab → Molecular sphere

The Astrophysical Journal, 579:446–454, 2002

Wavelength-dependent diameters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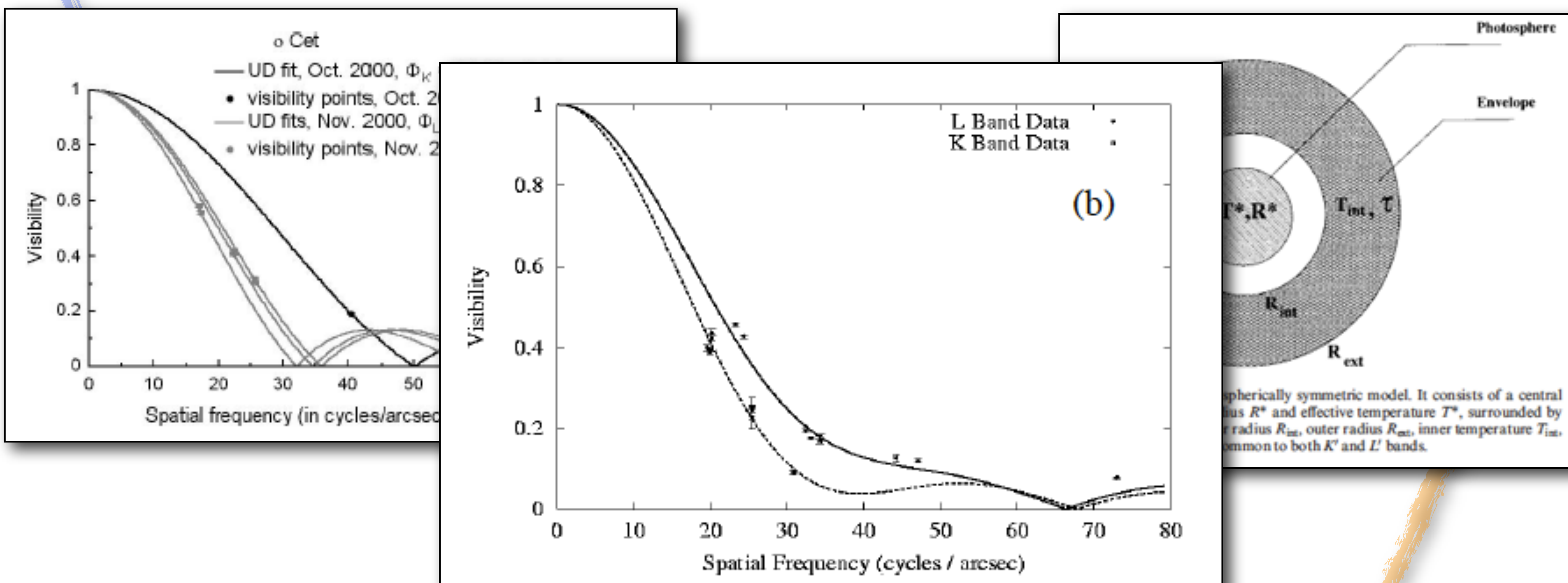


Molecular slab → Molecular sphere

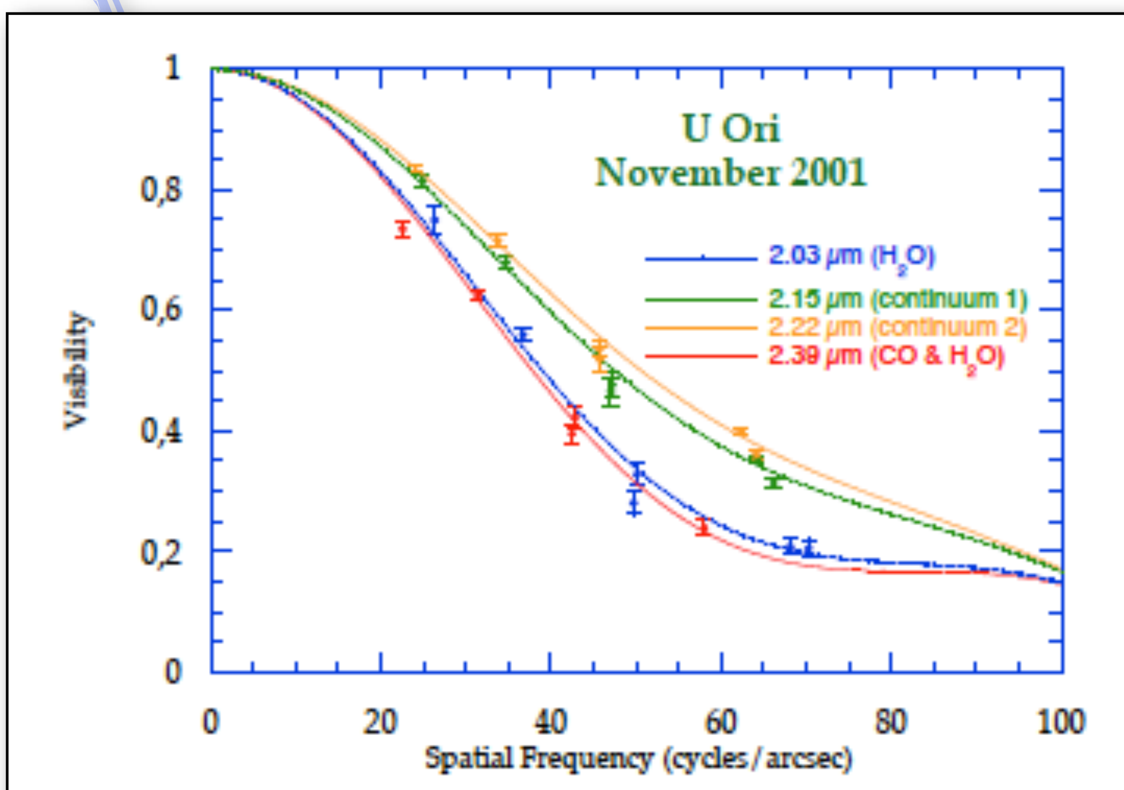
The Astrophysical Journal, 579:446–454, 2002

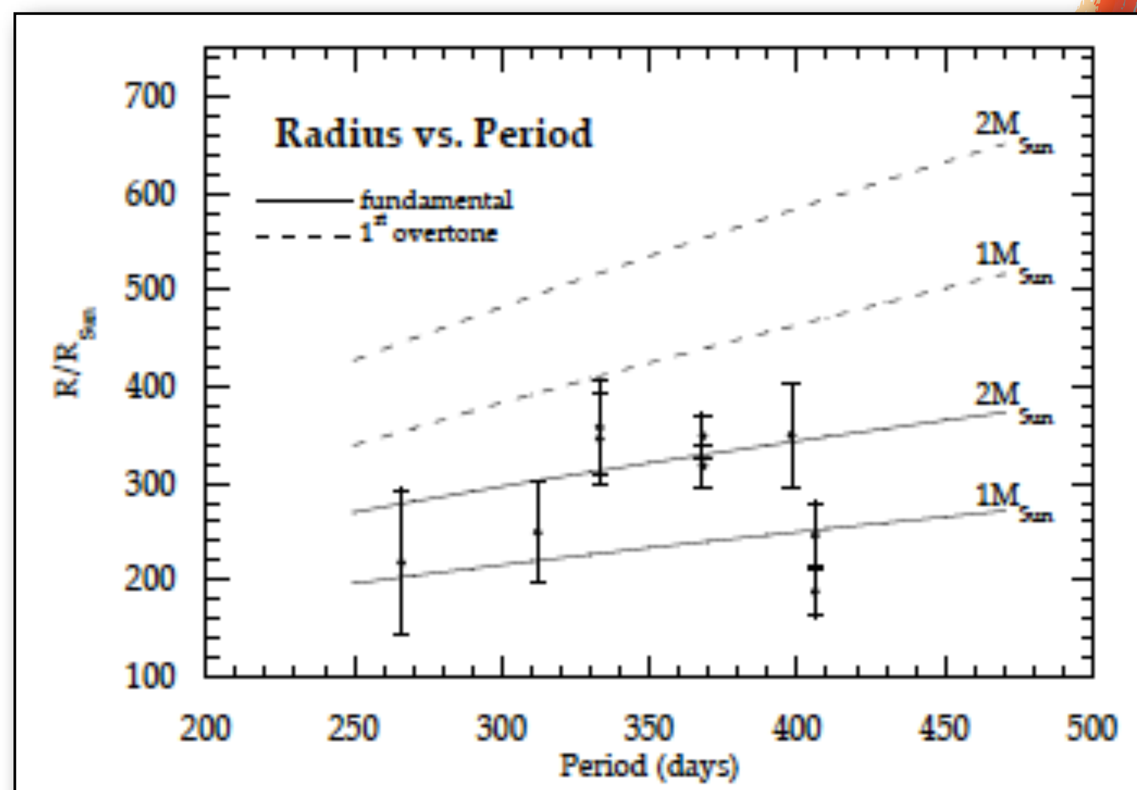
Wavelength-dependent diameters

Unveiling Mira stars behind the molecules★,★★

Confirmation of the molecular layer model with narrow band near-infrared interferometry

G. Perrin[1], S. T. Ridgway[1,2], B. Mennesson[3], W. D. Cotton[4], J. Woillez[1,5], T. Verhoelst[1,6], P. Schuller[7], V. Coudé du Foresto[1], W. A. Traub[7], R. Millan-Gabet[8], and M. G. Lacasse[7]





(Some) Mira stars pulsate in the fundamental mode

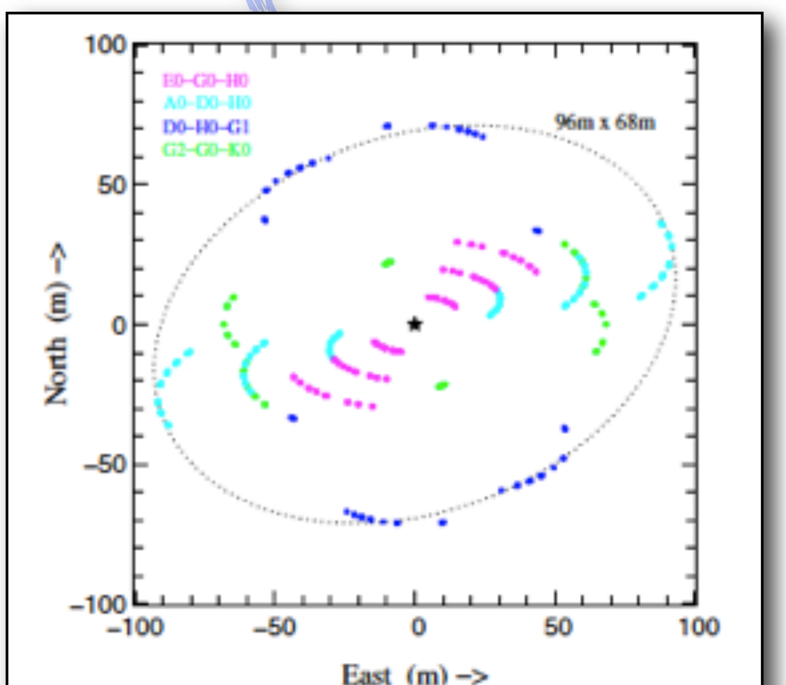
A&A 426, 279–296 (2004)

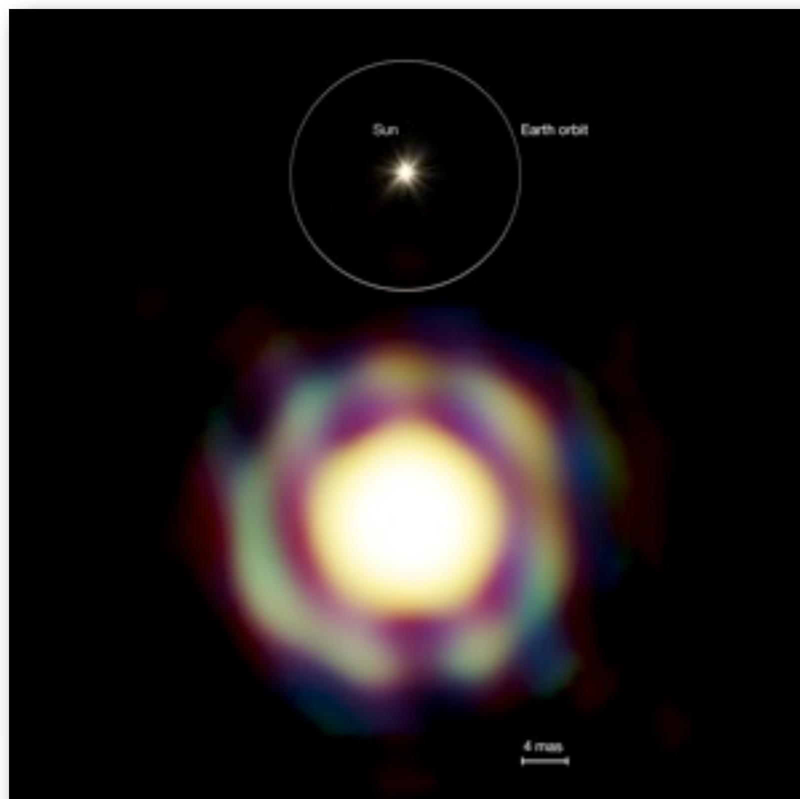
Wavelength-dependent diameters

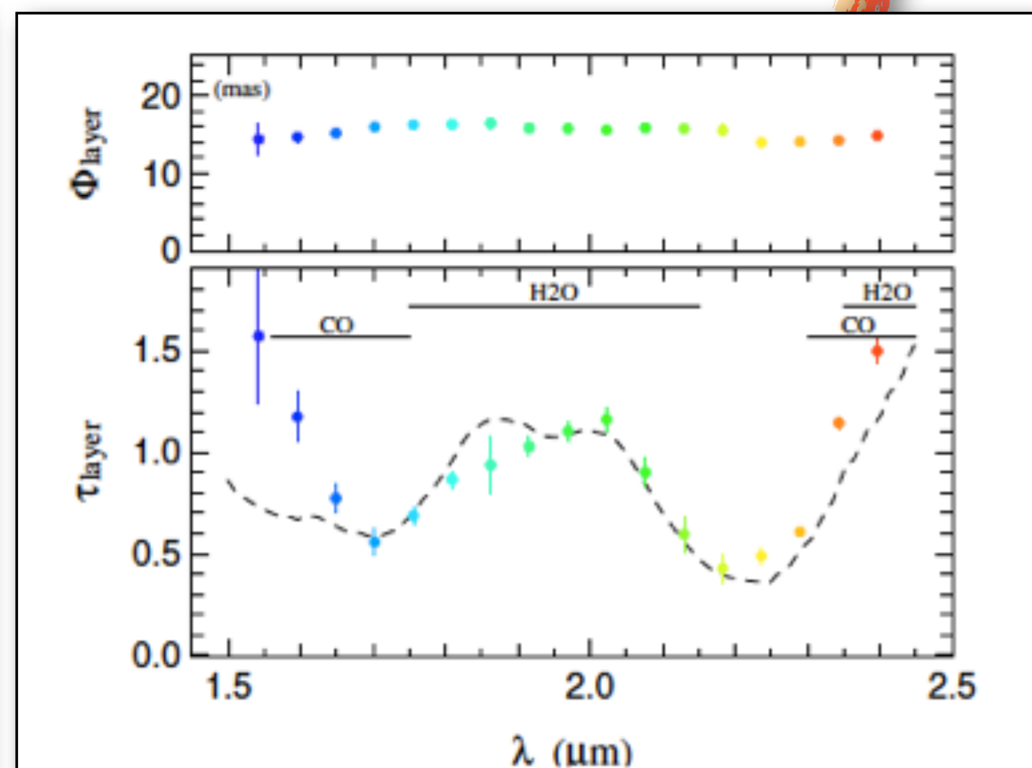
Letter to the Editor

Pre-maximum spectro-imaging of the Mira star T Leporis with AMBER/VLTI★

J.-B. Le Bouquin[1], S. Lacour[2], S. Renard[2], E. Thiébaut[3], A. Merand[1], and T. Verhoelst[4]







Confirmation of the validity of the Molsphere approximation!

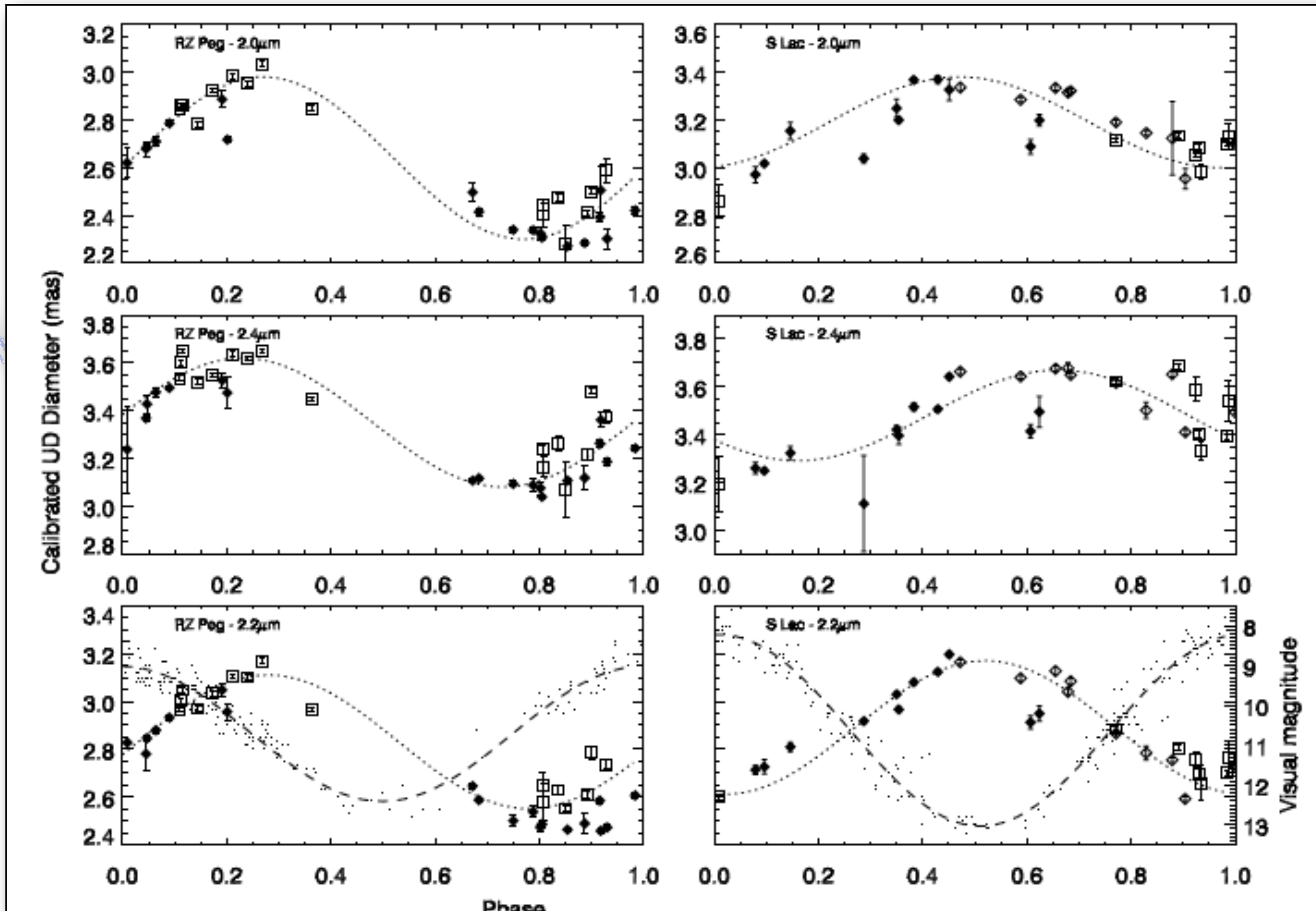
A&A 496, L1–L4 (2009)

Time-dependent diameters

MULTIEPOCH INTERFEROMETRIC STUDY OF MIRA VARIABLES. I. NARROWBAND DIAMETERS OF RZ PEGASI AND S LACERTAE

R. R. Thompson,[1,2] M. J. Creech-Eakman,[1,3] and G. T. van Belle[1]

Received 2002 January 8; accepted 2002 May 25



The Astrophysical Journal, 577:447–456, 2002

Time-dependent diameters

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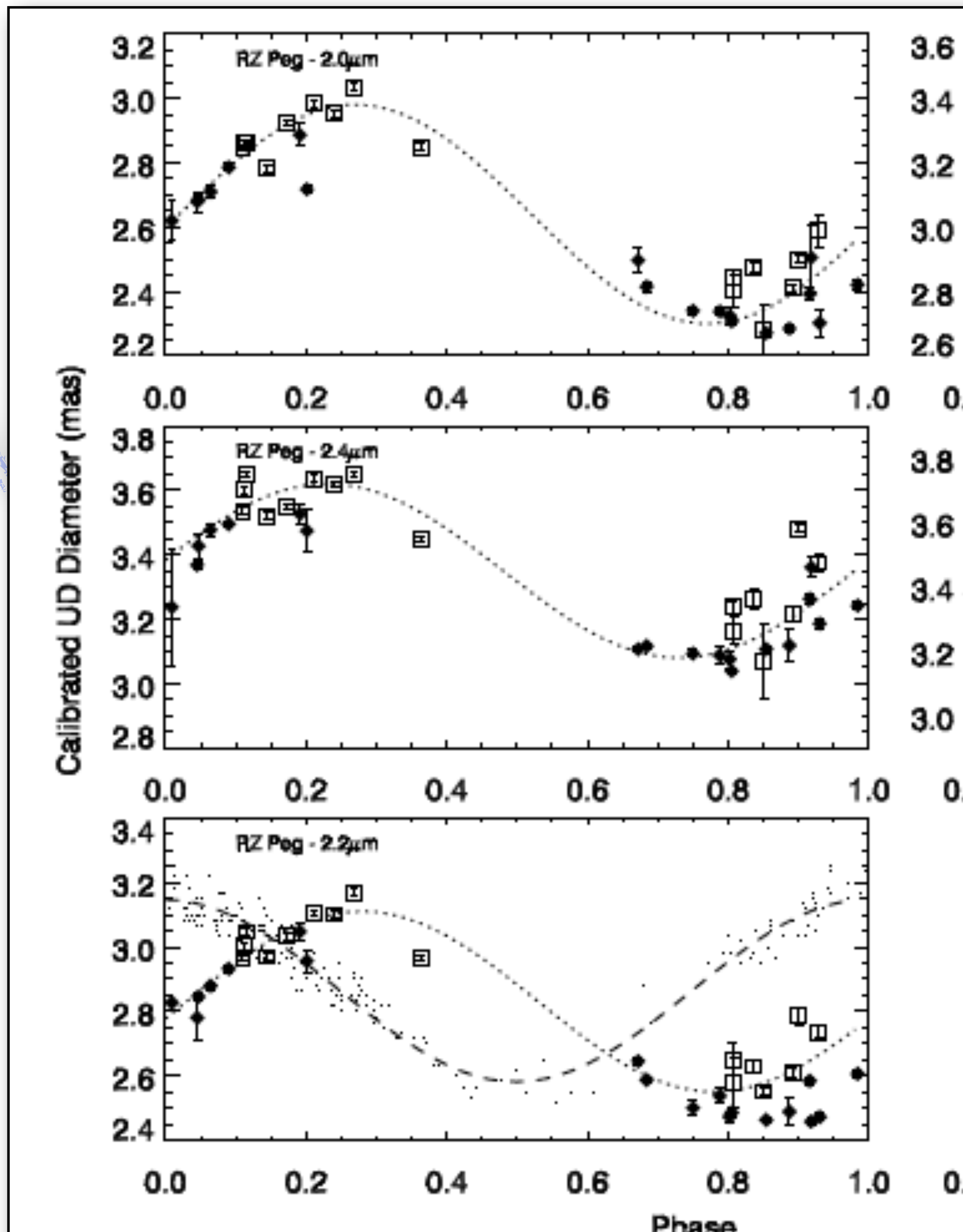


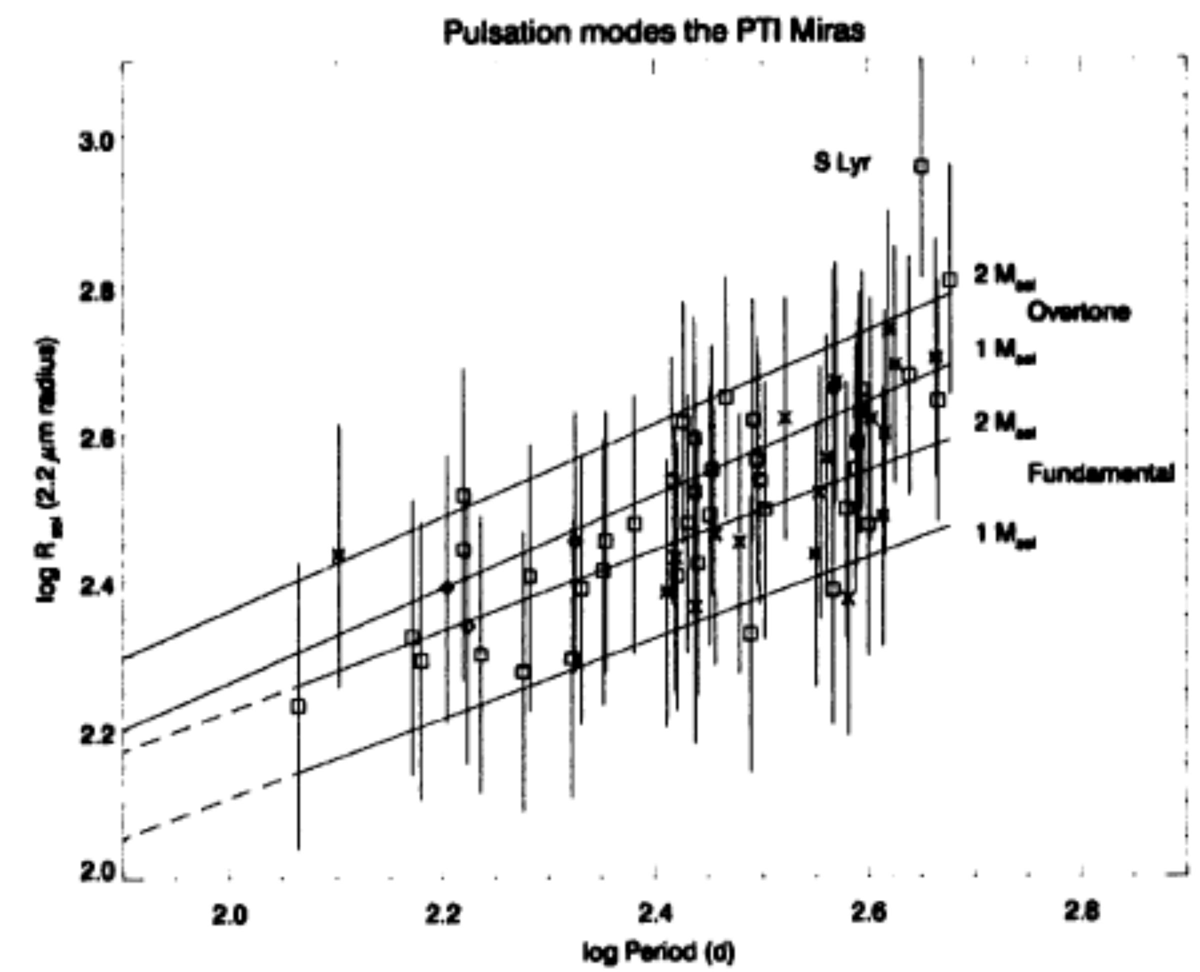


Figure 6.11 – The PTI Mira dataset, with values translated into logarithms. Symbols are the same as in Fig. 6.8. Also plotted are the theoretical lines of fundamental and first-overtone for 1 and 2 $M_\odot$ pulsators.

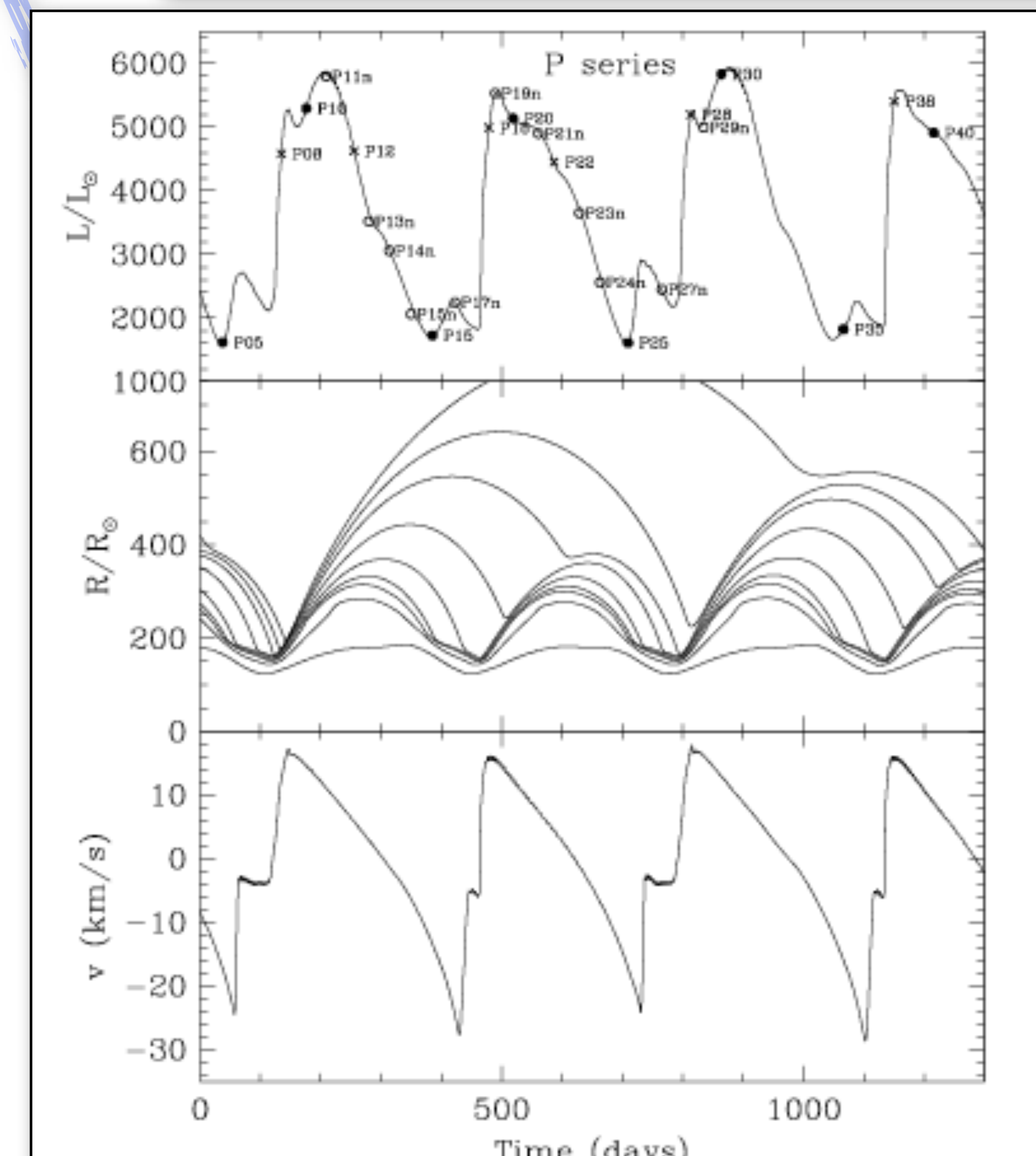
The Astrophysical Journal, 577:447–456, 2002

Time-dependent diameters

On the observability of geometric pulsation of M-type Mira variables

M. J. Ireland,[1★] M. Scholz[1,2] and P. R. Wood[3]
[1]*School of Physics, University of Sydney, NSW 2006, Australia*
[2]*Institut für Theoretische Astrophysik der Universität Heidelberg, Tiergartenstr. 15, 69121 Heidelberg, Germany*
[3]*Research School for Astronomy and Astrophysics, Australian National University, Canberra, ACT 2600, Australia*

Mon. Not. R. Astron. Soc. **352**, 318-324 (2004)



Also used for limb-darkening predictions (Hofmann et al. 1998)

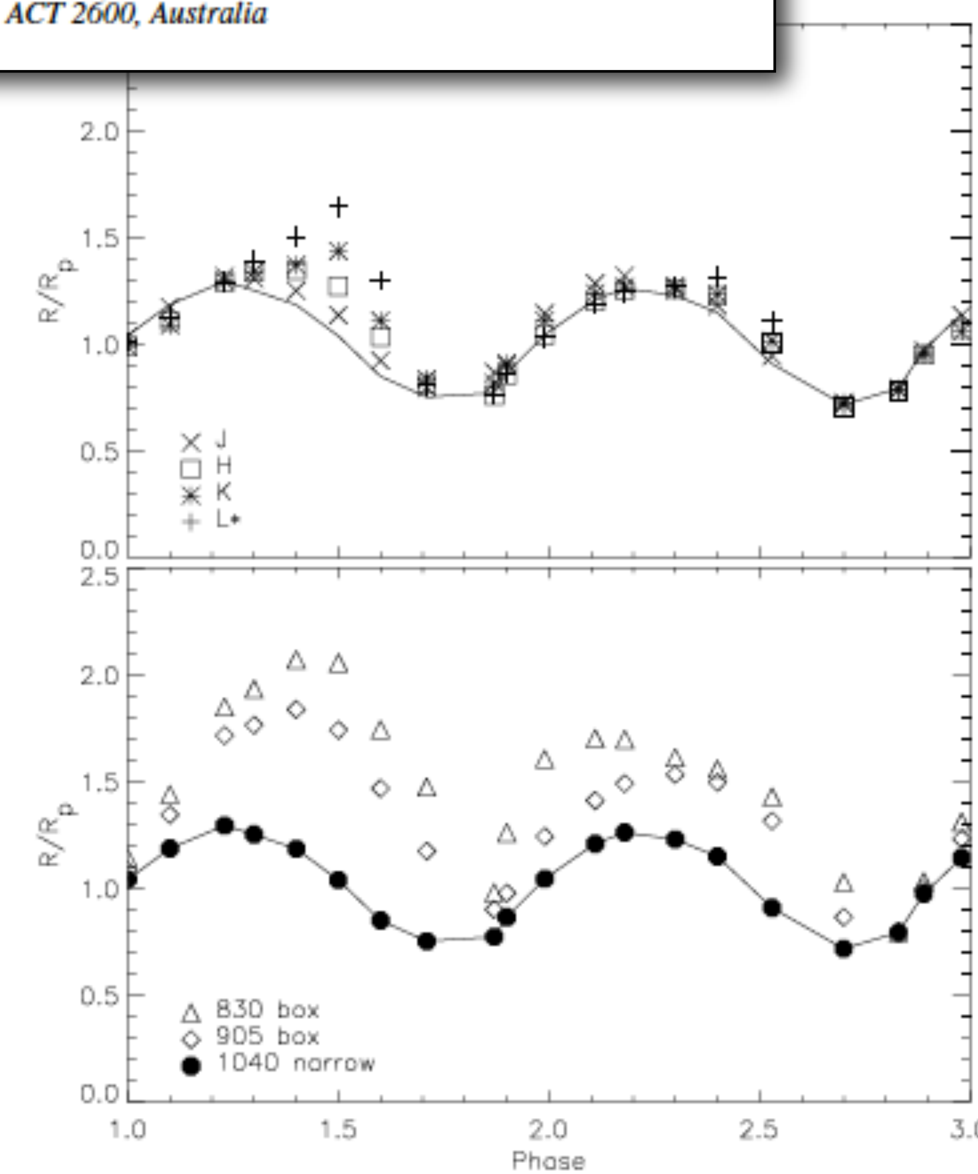
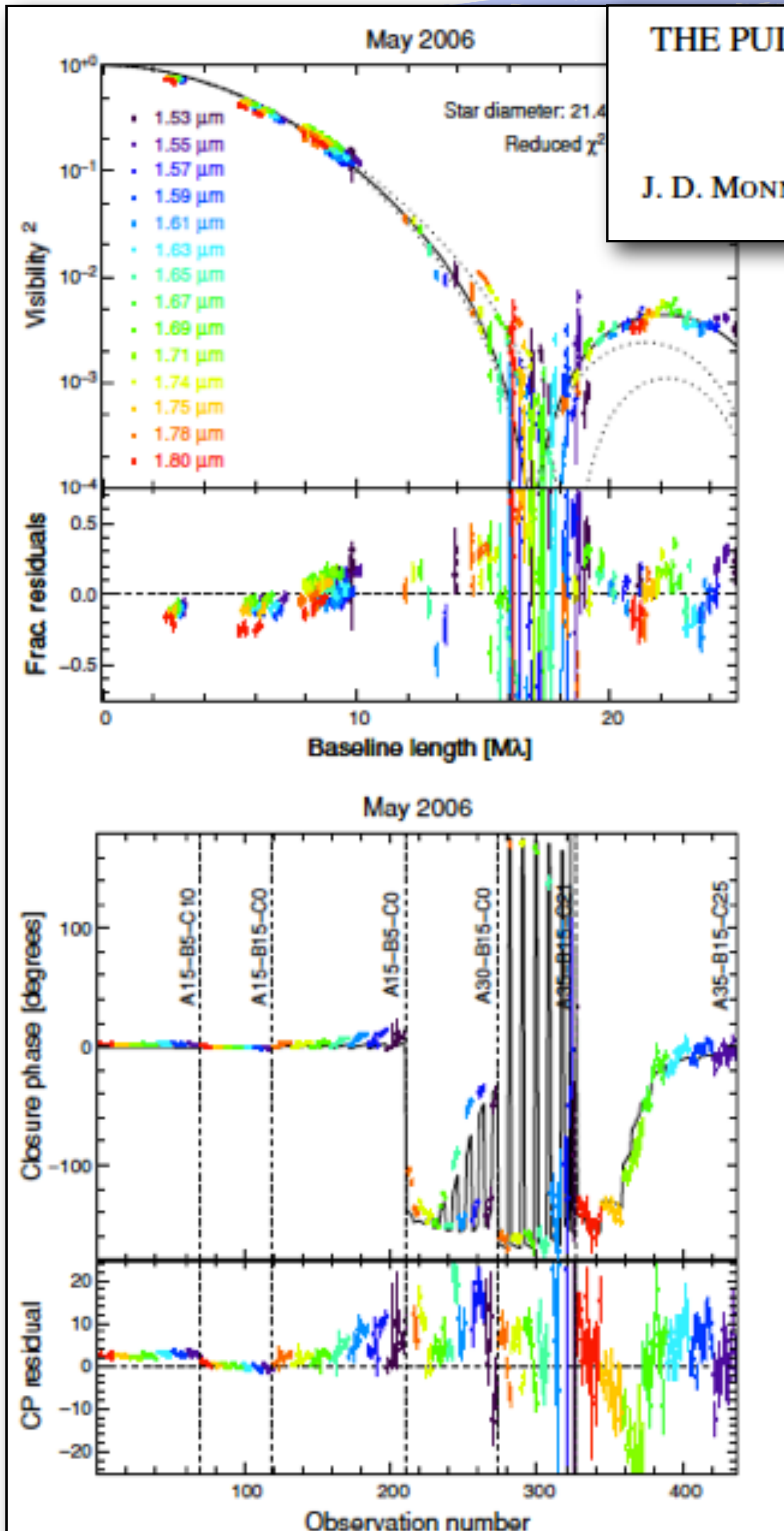


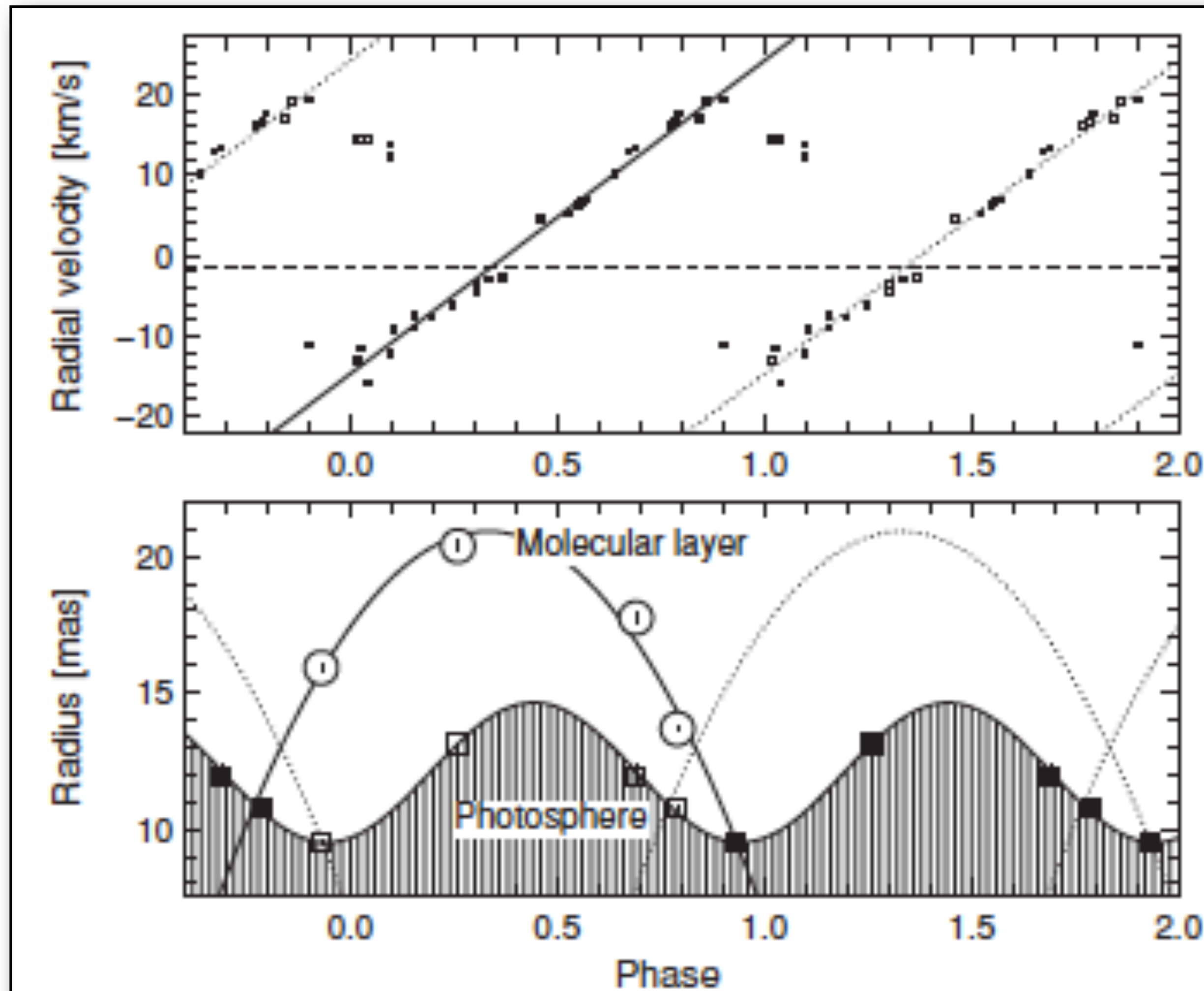
Figure 4. Phase variation of filter radii in units of the parent star radius R_p in seven near-continuum bandpasses (see text). In both the upper and lower panels the points of the 1.04-μm continuum bandpass defining the $R_{1.04}$ radius are connected by the full line.

Time-dependent diameters



THE PULSATION OF χ CYGNI IMAGED BY OPTICAL INTERFEROMETRY: A NOVEL TECHNIQUE TO DERIVE DISTANCE AND MASS OF MIRA STARS

S. Lacour[1], E. Thiébaut[2], G. Perrin[1], S. Meimon[3], X. Haubois[1], E. Pedretti[4], S. T. Ridgway[5], J. D. Monnier[6], J. P. Berger[7], P. A. Schuller[8], H. Woodruff[9], A. Poncelet[1], H. Le Coroller[10], R. Millan-Gabet[11], M. Lacasse[12], and W. Traub[13]

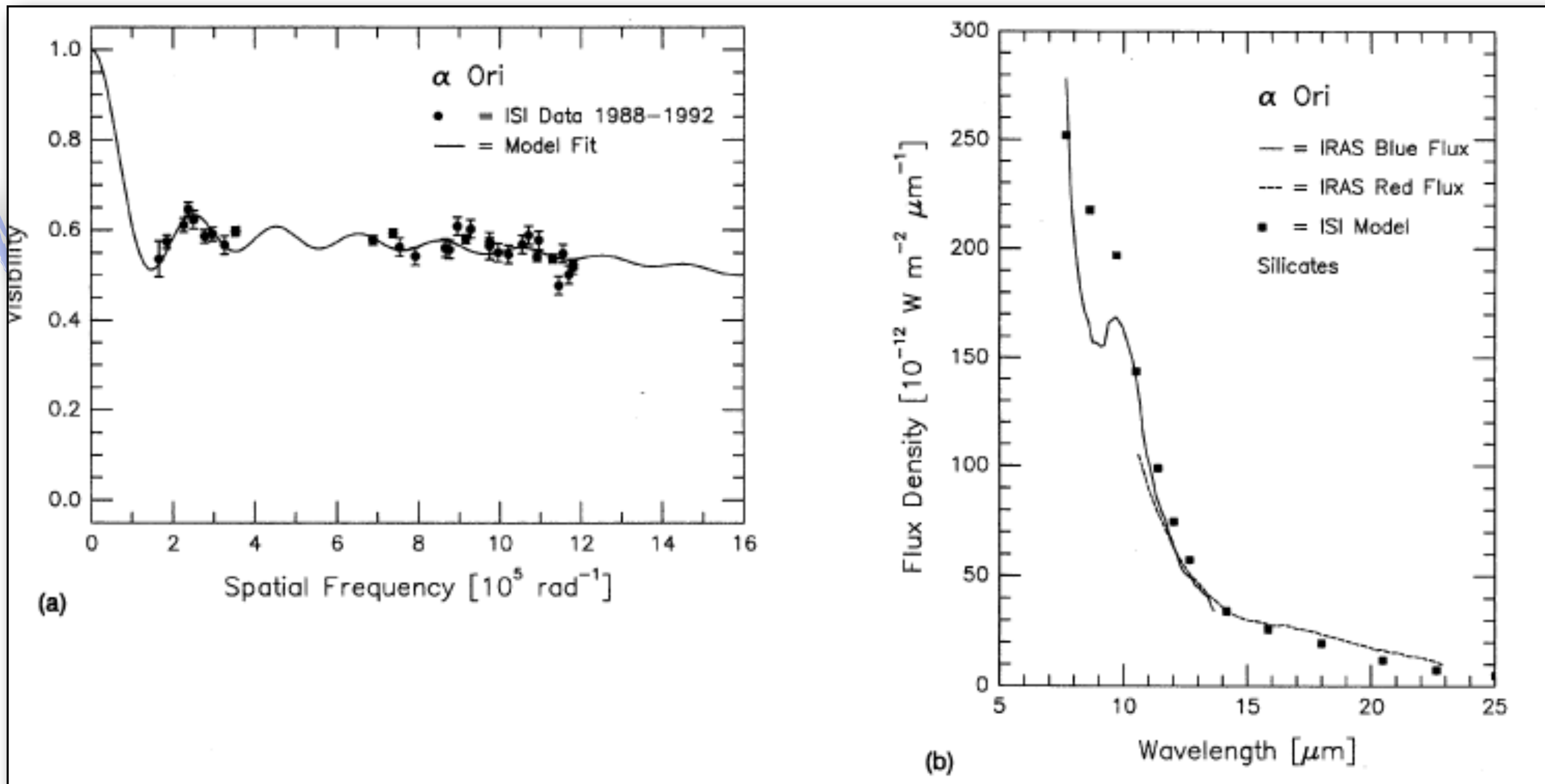


The Astrophysical Journal, 707:632–643, 2009

Circumstellar dust: outflows

CHARACTERISTICS OF DUST SHELLS AROUND 13 LATE-TYPE STARS

W. C. DANCHI, M. BESTER, C. G. DEGIACOMI,[1] L. J. GREENHILL,[2] AND C. H. TOWNES
Space Sciences Laboratory and Physics Department, University of California at Berkeley, Berkeley, California 94720
Received 1993 October 13; revised 1993 December 16



Astron. J. **107** (4), April 1994

Circumstellar dust: outflows

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Space Sciences Laboratory and Physics Department, University of California at Berkeley, Berkeley, California 94720
Received 1993 October 13; revised 1993 December 16

TABLE 10. Inner radii of dust shells of recently observed stars.

Star	Phase	r_0 (″)	r_0/r_*	T_0 (K)	τ_{11}	Maser SiO	H_2O	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

Astron. J. **107** (4), April 1994

Circumstellar dust: outflows

Dust scattering in the Miras R Car and RR Sco resolved by optical interferometric polarimetry

M. J. Ireland,[★] P. G. Tuthill, J. Davis and W. Tango
School of Physics, University of Sydney, Sydney, NSW 2006, Australia

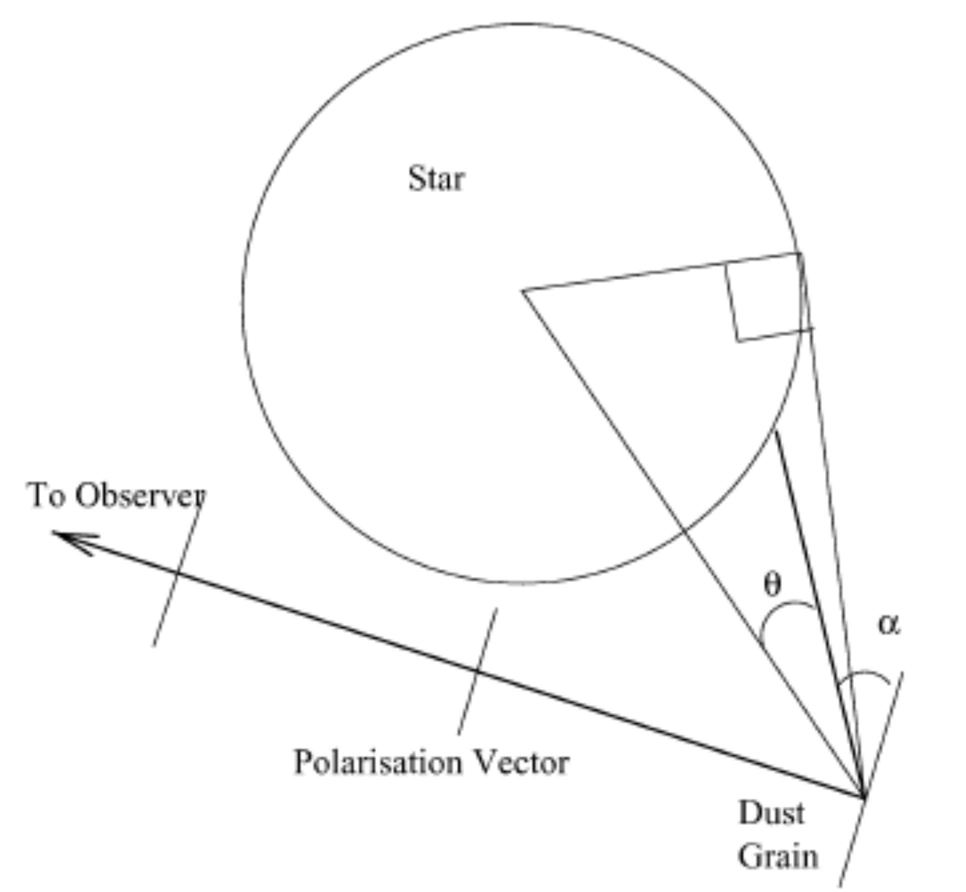


Figure 3. An example of the geometry for which the polarized intensity was calculated, using the approximation of Rayleigh scattering from an optically thin shell (see text).

5 CONCLUSION

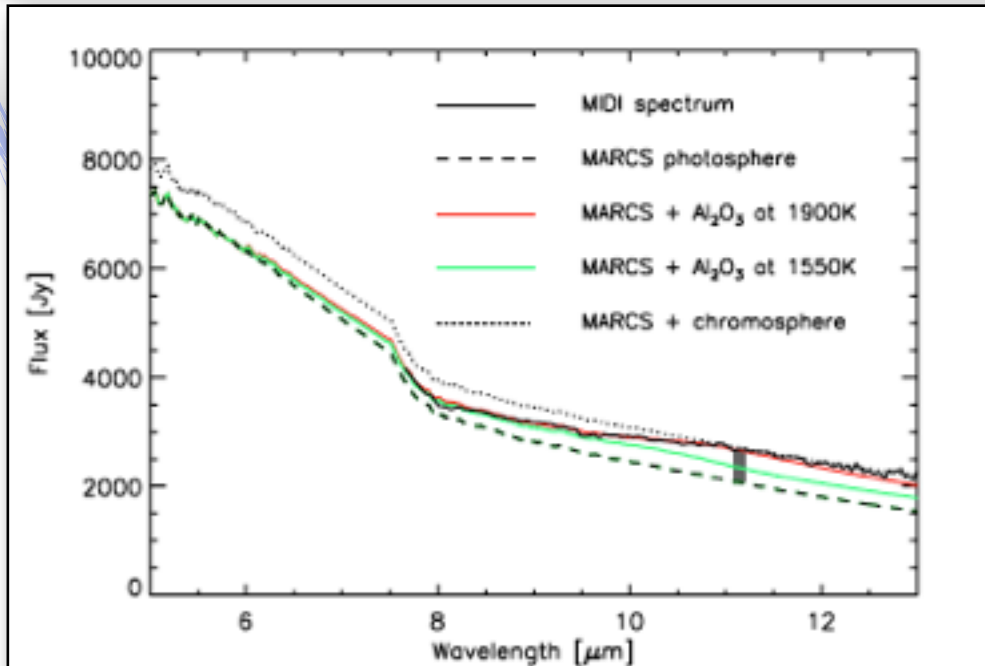
Using optical interferometric polarimetry, we have spatially separated the component of flux at 900 nm scattered by dust around the Mira variables R Car and RR Sco from their photospheric emission. We found that the inner radius of dust formation around these stars to be less than three stellar radii, consistent with dust that is relatively transparent between 1 and 4 μm, such as iron-poor silicates or corundum. This dust exists in a shell-like structure around these

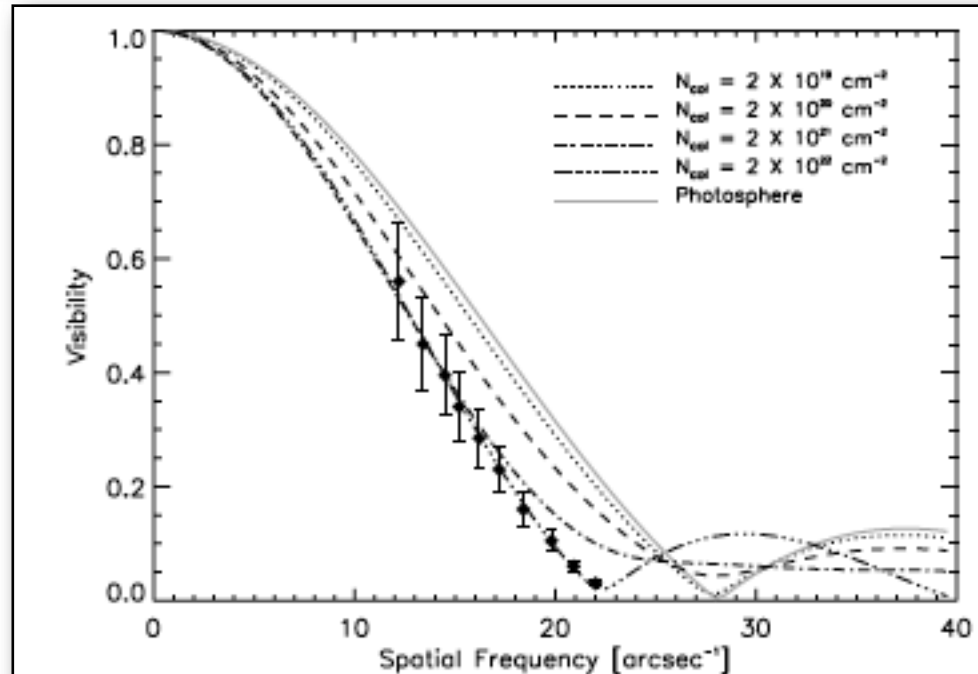
Mon. Not. R. Astron. Soc. **361,** 337–344 (2005)

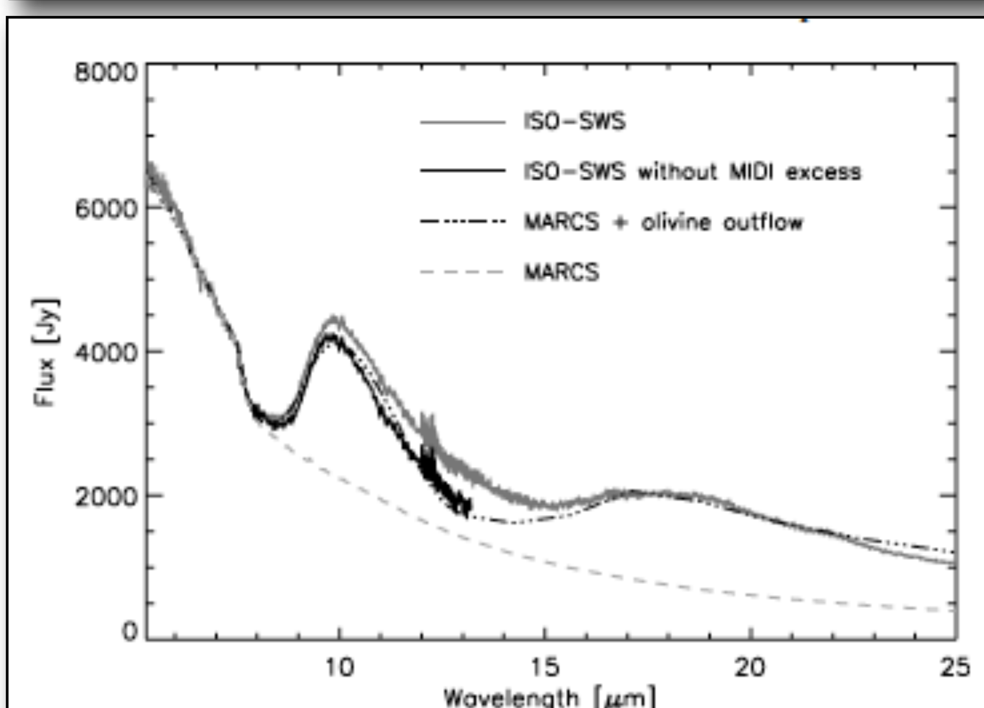
Circumstellar dust: outflows

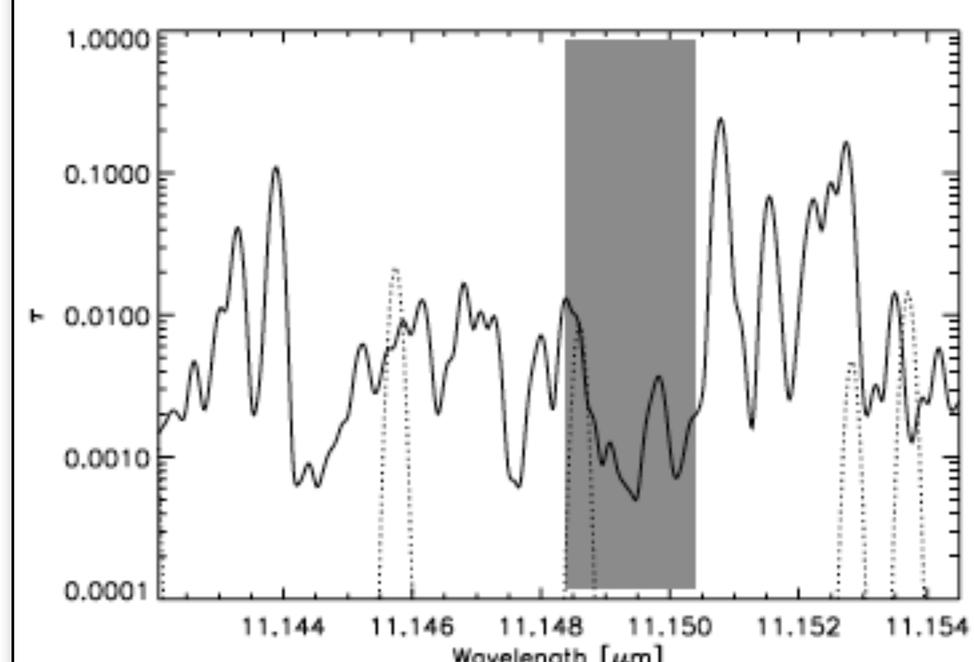
Amorphous alumina in the extended atmosphere of α Orionis

T. Verhoelst[1,2,⋆], L. Decin[1,⋆], R. Van Malderen[1], S. Hony[1], J. Cami[3], K. Eriksson[4], G. Perrin[2], P. Deroo[1], B. Vandenbussche[1], and L. B. F. M. Waters[1,5]









A&A 447, 311–324 (2006)

Circumstellar dust: outflows

Temporal variations of the outer atmosphere and the dust shell of the carbon-rich Mira variable V Ophiuchi probed with VLTI/MIDI⋆,⋆⋆

K. Ohnaka[1], T. Driebe[1], G. Weigelt[1], and M. Wittkowski[2]

A&A 466, 1099–1110 (2007)

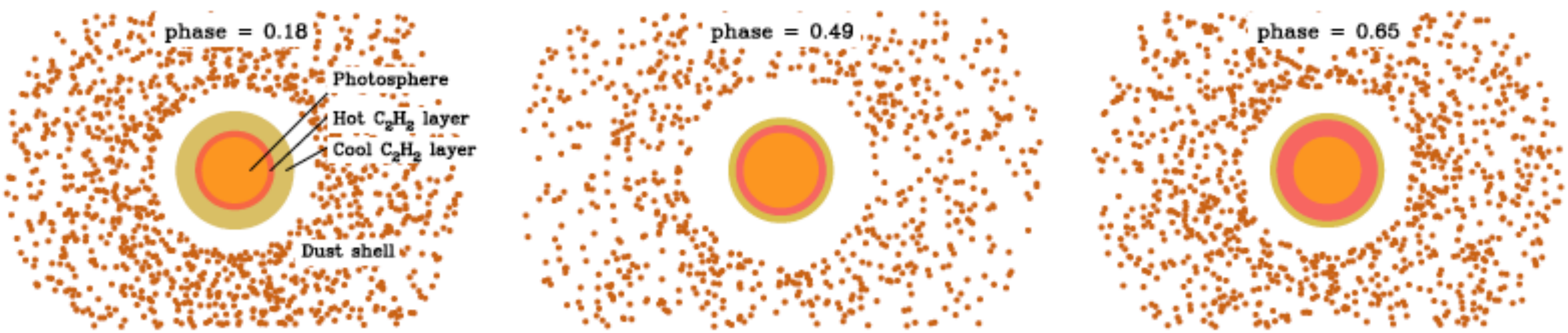


Fig. 10. A simple cartoon illustrating the best-fit models at phases 0.18, 0.49, and 0.65. The sizes of the components at three phases *are to scale* except for the outer radius of the dust shell.

Observing and modeling the dynamic atmosphere of the low mass-loss C-star R Sculptoris at High Angular Resolution⋆

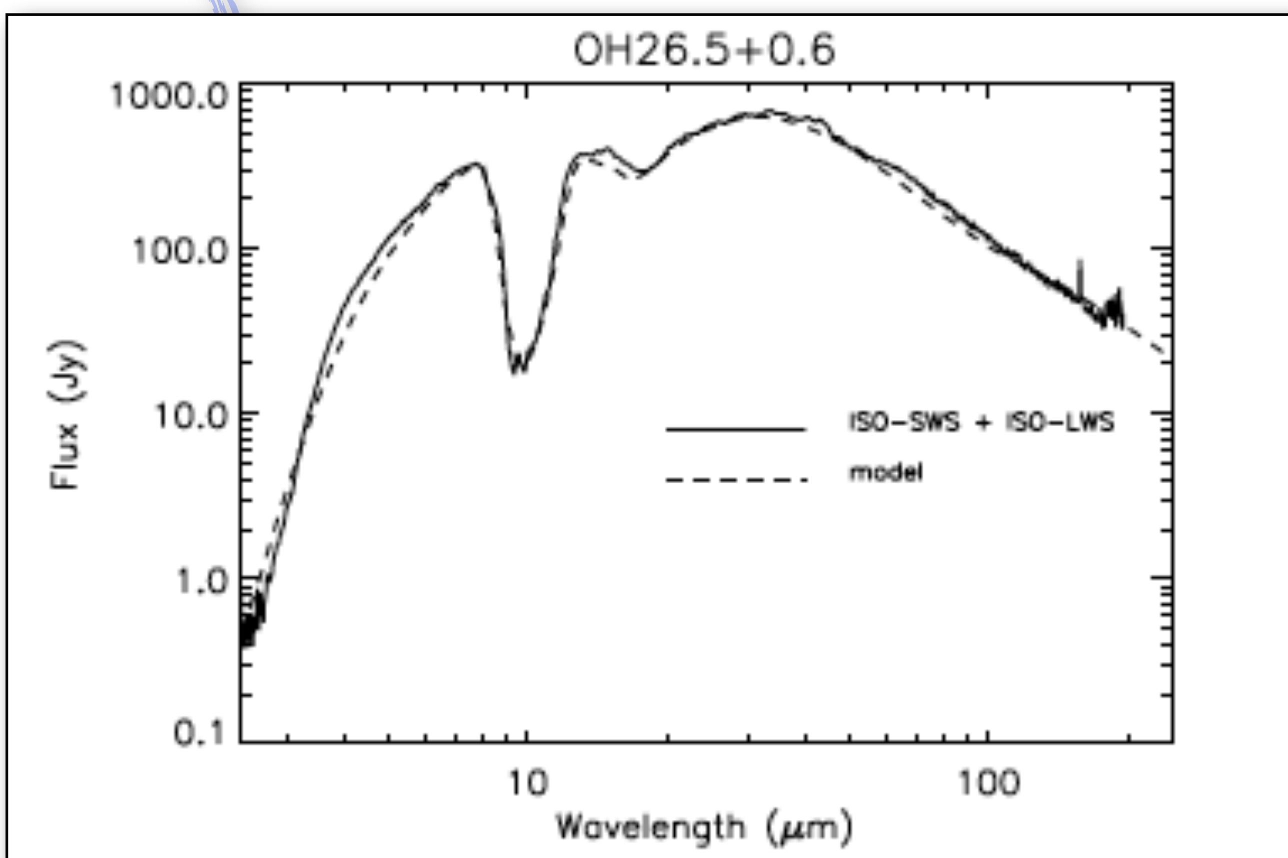
S. Sacuto[1], B. Aringer[2], J. Hron[1], W. Nowotny[1], C. Paladini[1], T. Verhoelst[3], and S. Höfner[4]

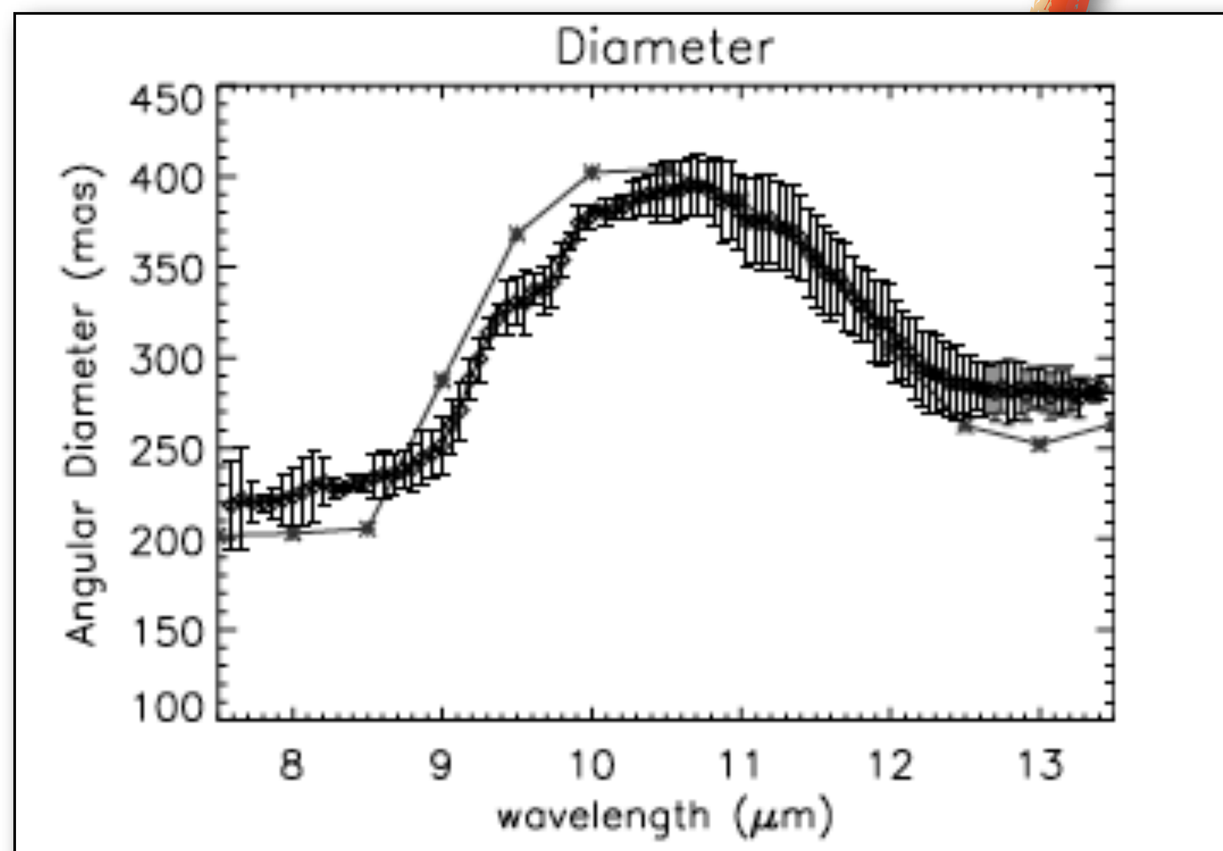
A&A, submitted

Circumstellar dust: outflows

The mid-IR spatially resolved environment of OH 26.5+0.6 at maximum luminosity★

O. Chesneau[1], T. Verhoelst[2], B. Lopez[3], L. B. F. M. Waters[2,4], Ch. Leinert[1], W. Jaffe[5],
R. Köhler[1], A. de Koter[4], and C. Dijkstra[4]



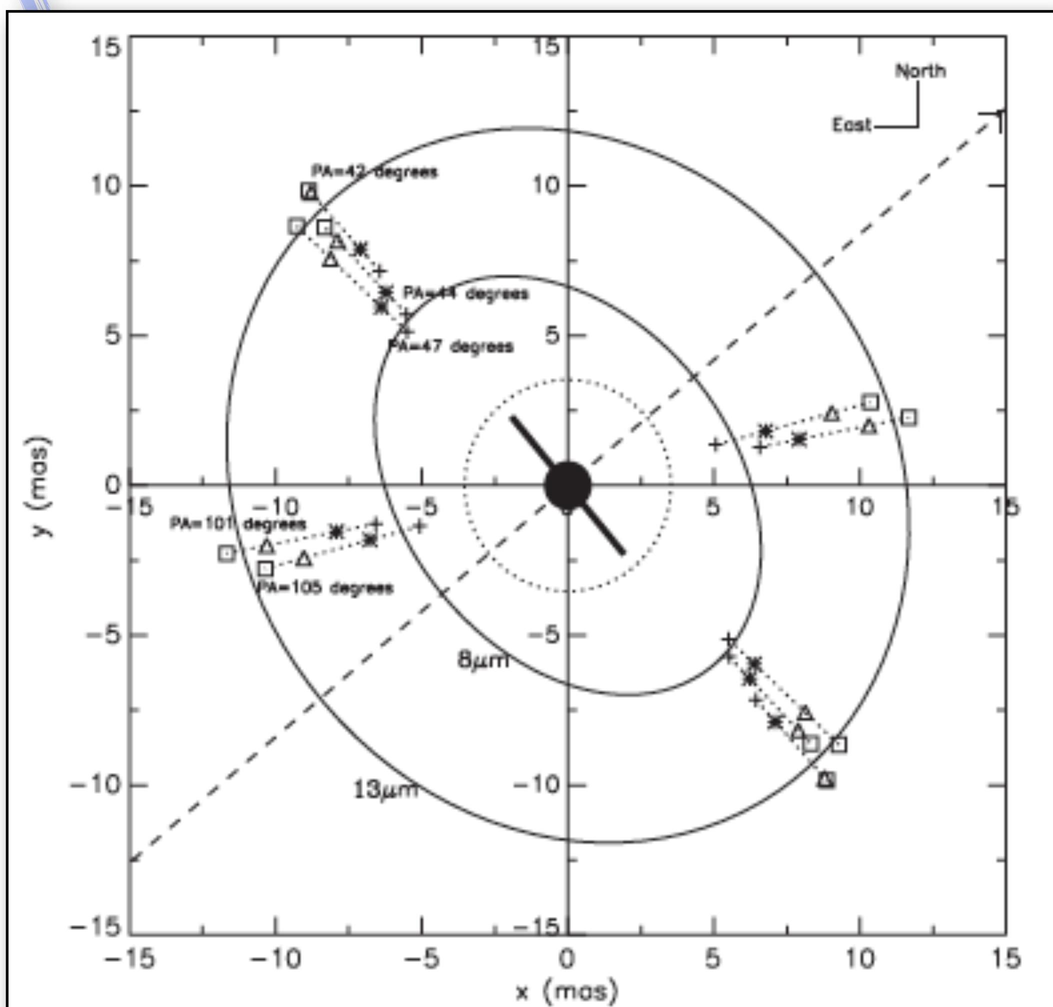


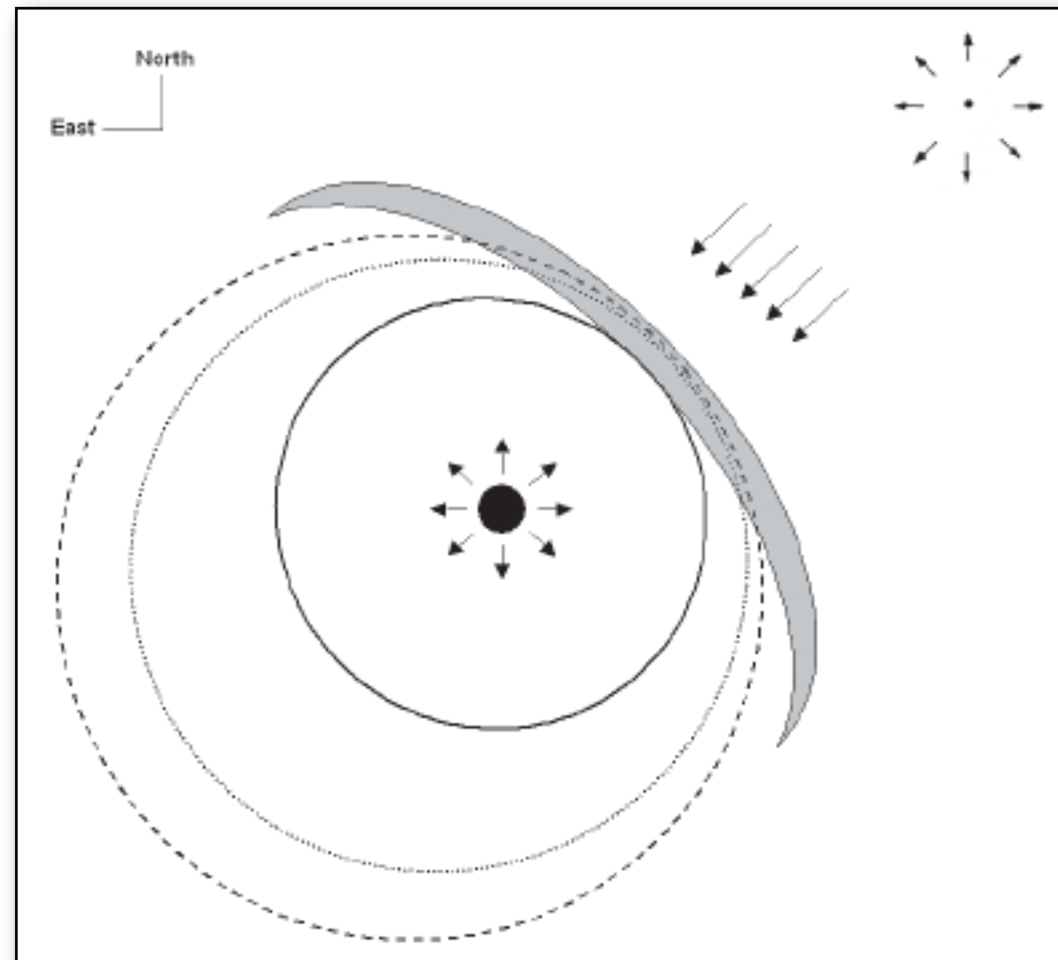
A&A 435, 563–574 (2005)

Circumstellar dust: outflows

A compact dust shell in the symbiotic system HM Sagittae★,★★,★★★

S. Sacuto[1], O. Chesneau[1], M. Vannier[2], and P. Cruzalèbes[1]



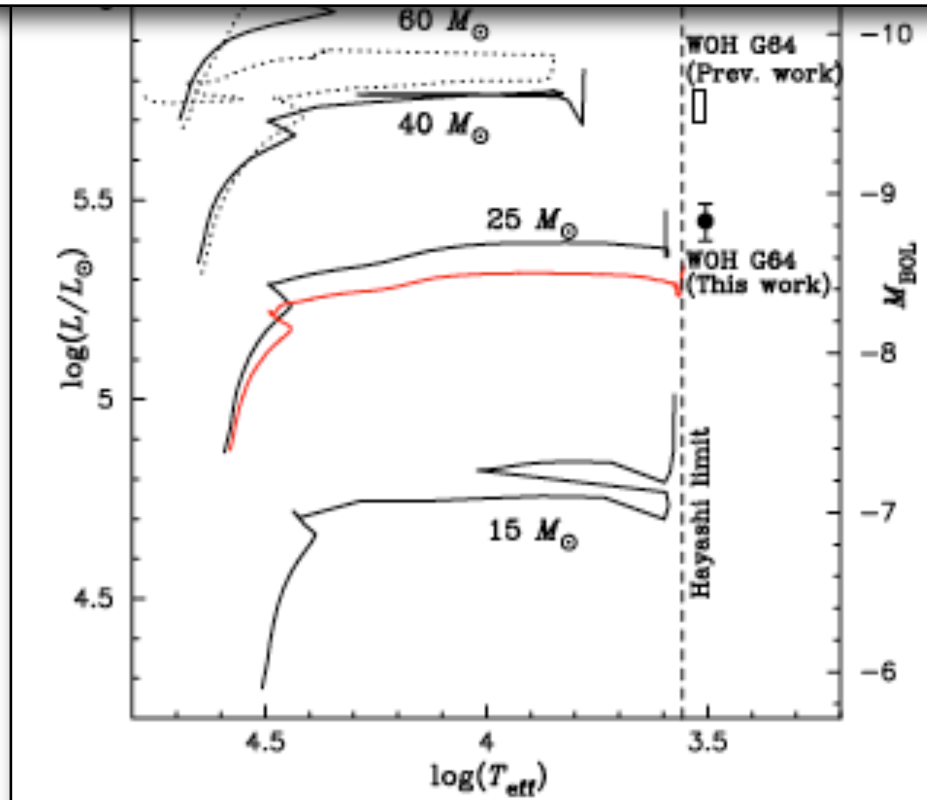


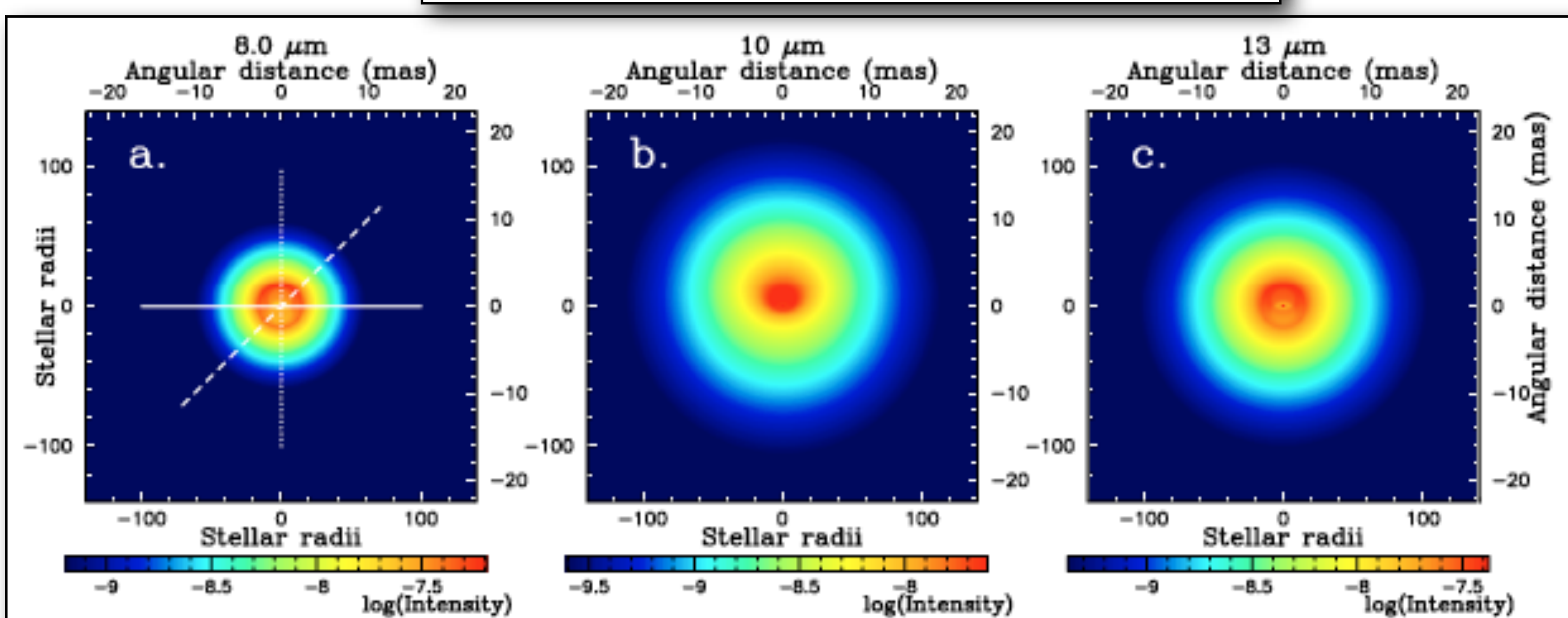
A&A 465, 469–480 (2007)

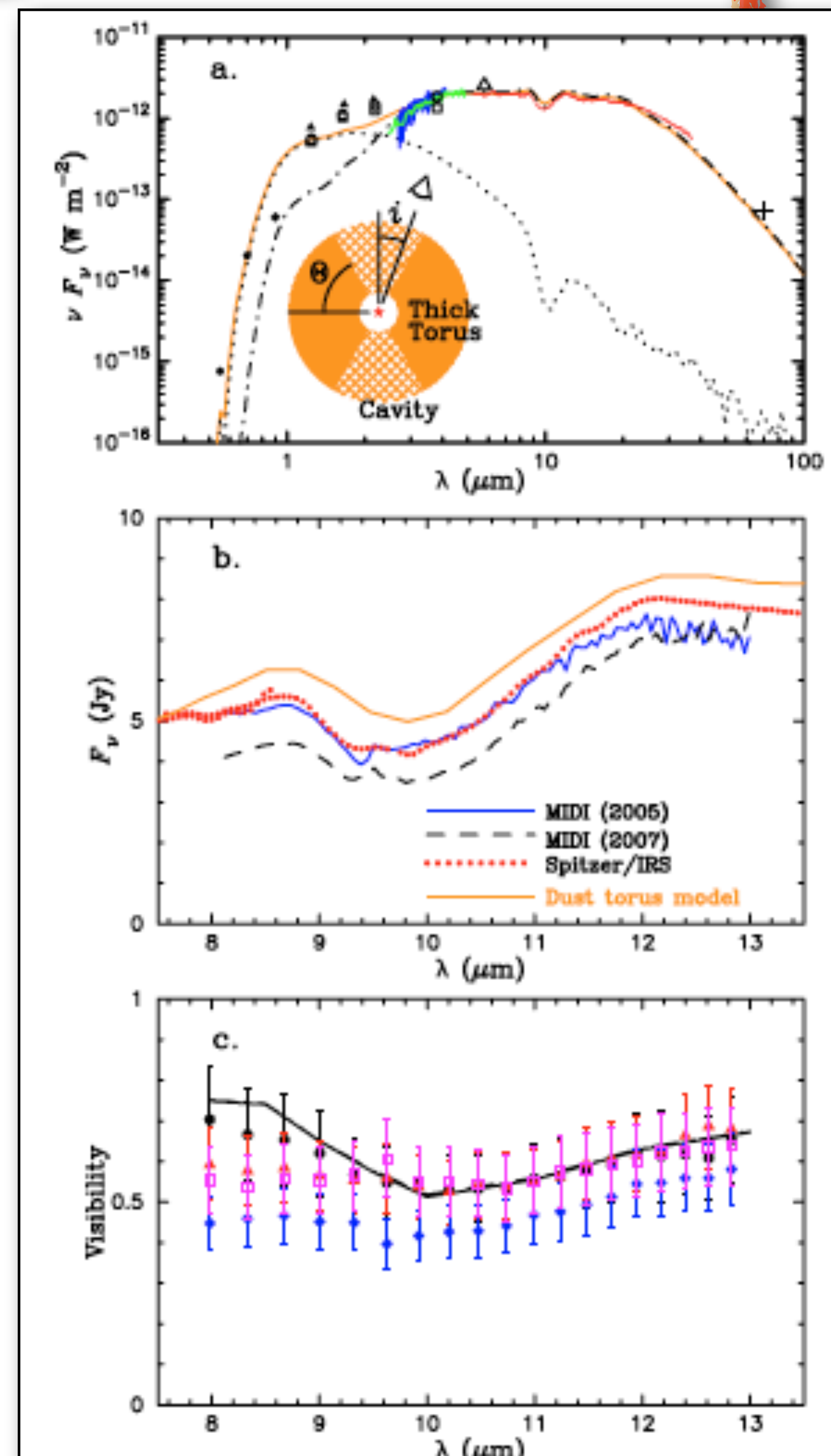
Circumstellar dust: torii

Spatially resolved dusty torus toward the red supergiant WOH G64 in the Large Magellanic Cloud★,★★

K. Ohnaka[1], T. Driebe[1], K.-H. Hofmann[1], G. Weigelt[1], and M. Wittkowski[2]







A&A 484, 371–379 (2008)

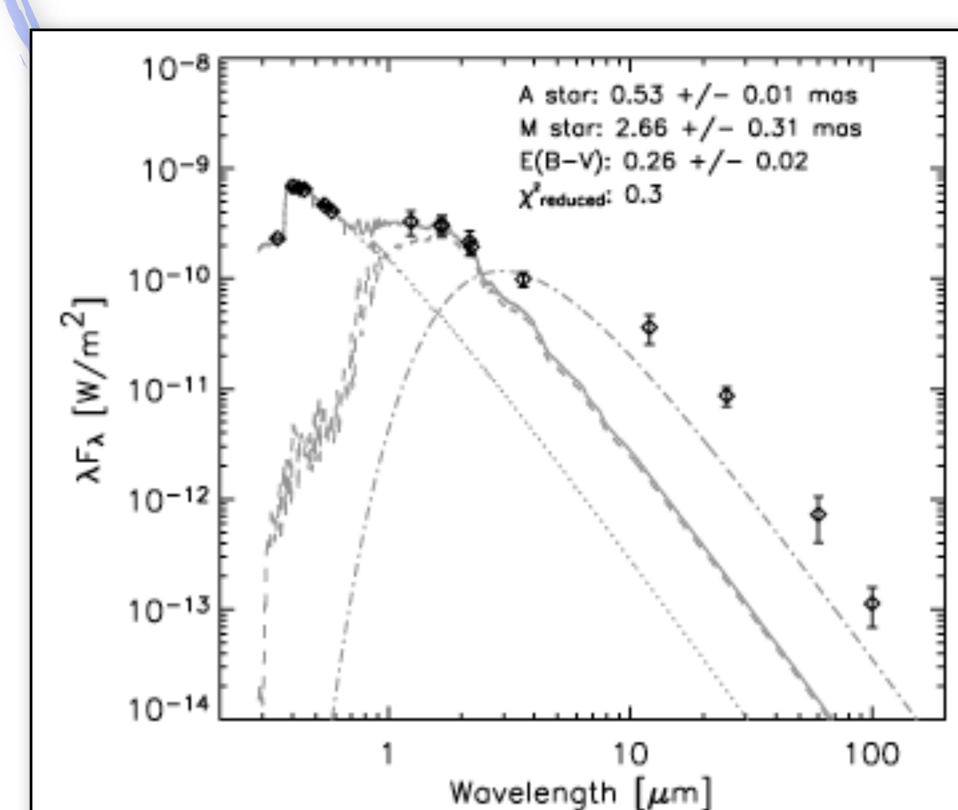
Circumstellar dust: (stable?) disks: RGB

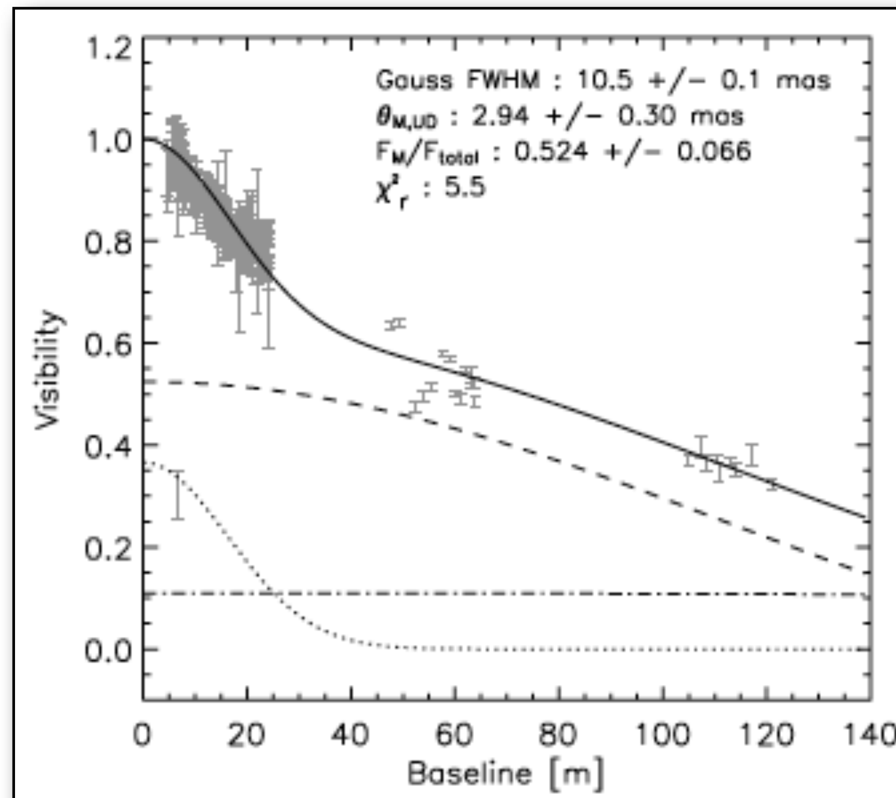
LETTER TO THE EDITOR

Direct diameter measurement of a star filling its Roche lobe

The semi-detached binary SS Leporis spatially resolved with VINCI/VLTI

T. Verhoelst*, E. van Aarle, and B. Acke*





A&A 470, L21–L24 (2007)

Circumstellar dust: (stable?) disks: RGB

LETTER TO THE EDITOR

Direct diameter measurement of a star filling its Roche lobe

The semi-detached binary SS Leporis spatially resolved with VINCI/VLTI

T. Verhoelst*, E. van Aarle, and B. Acke*

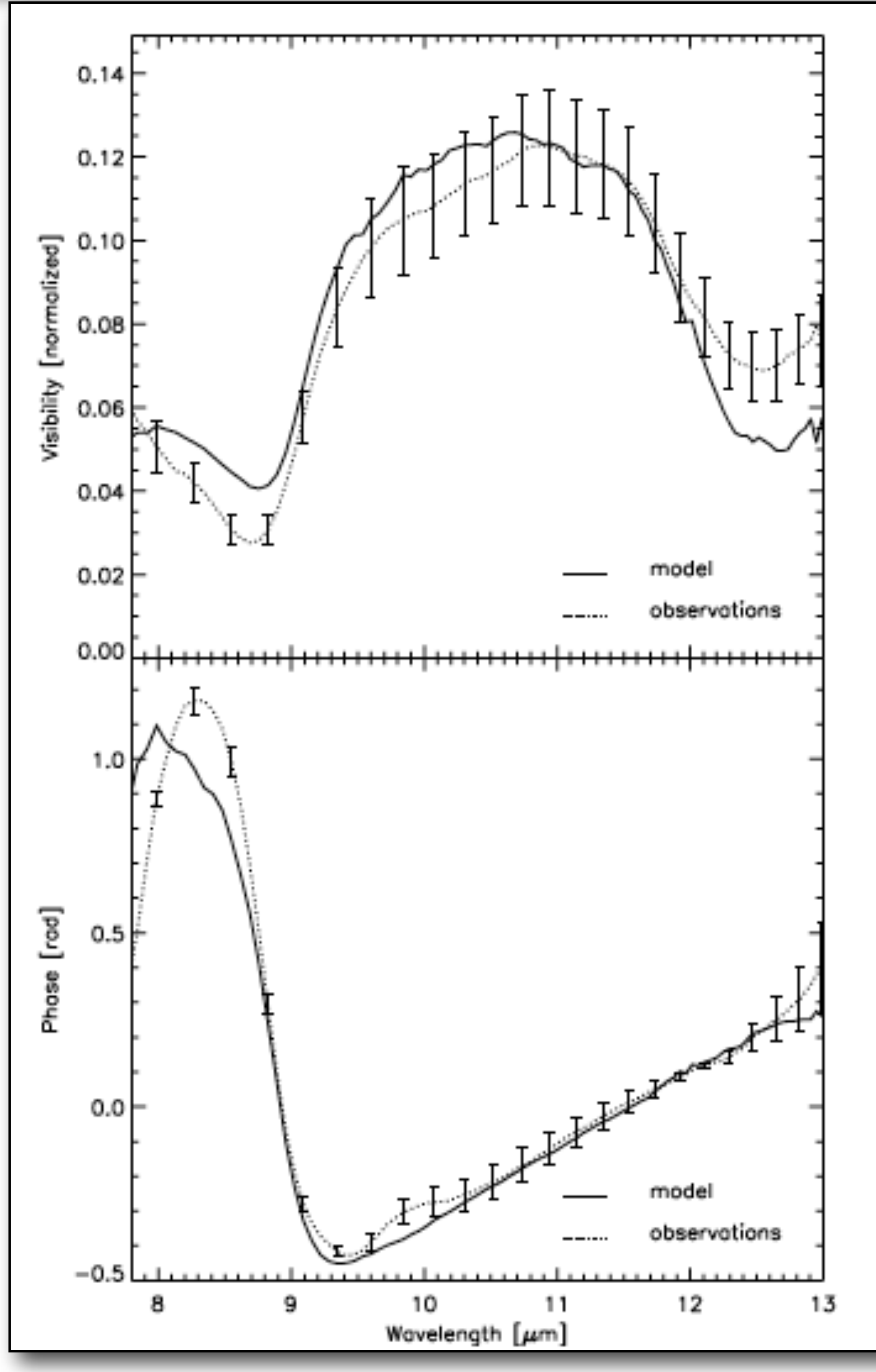
A&A 470, L21–L24 (2007)

Circumstellar dust: (stable?) disks: AGB

The circumbinary disc around the J-type C-star IRAS 18006-3213★

P. Deroo[1], H. Van Winckel[1], T. Verhoelst[1], M. Min[2], M. Reyniers[1], and L. B. F. M. Waters[1,2]

- The stability of the *N*-band spectrum and the observation that the circumstellar environment consists of highly processed silicate grains both indicate the existence of a long-lived reservoir in the system where the processing occurred.
- The interferometric observations show the very compact nature of the *N*-band emission, again providing strong evidence that this emission originates from a long-lived Keplerian disc.
- The interferometric observations show an asymmetric *N*-band emission. This provides direct evidence of the non-spherical nature of the emission.



Similar results by Ohnaka et al. (2008) on BM Geminorum

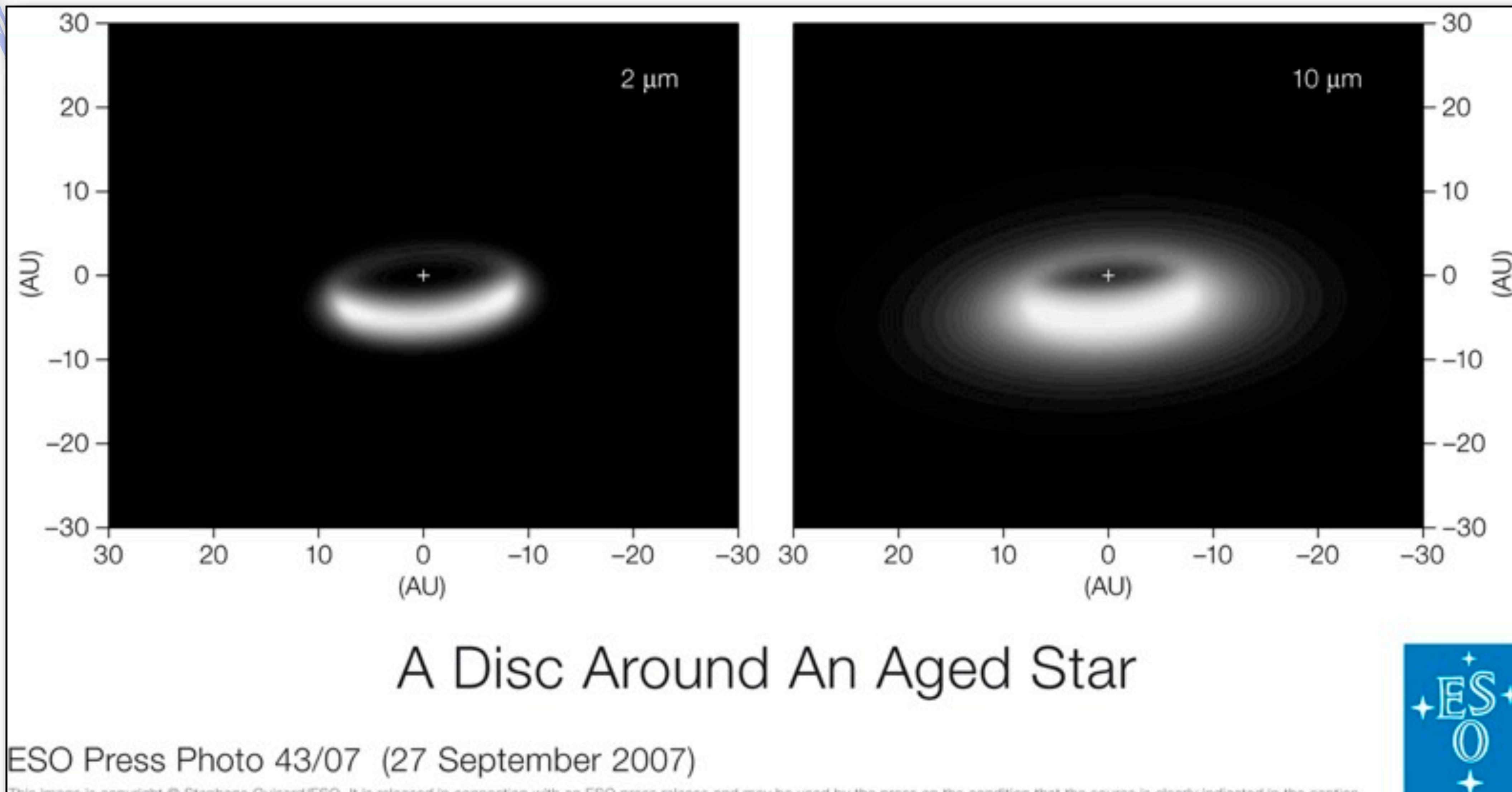
A&A 467, 1093–1101 (2007)

Circumstellar dust: (stable?) disks: Post-AGB

LETTER TO THE EDITOR

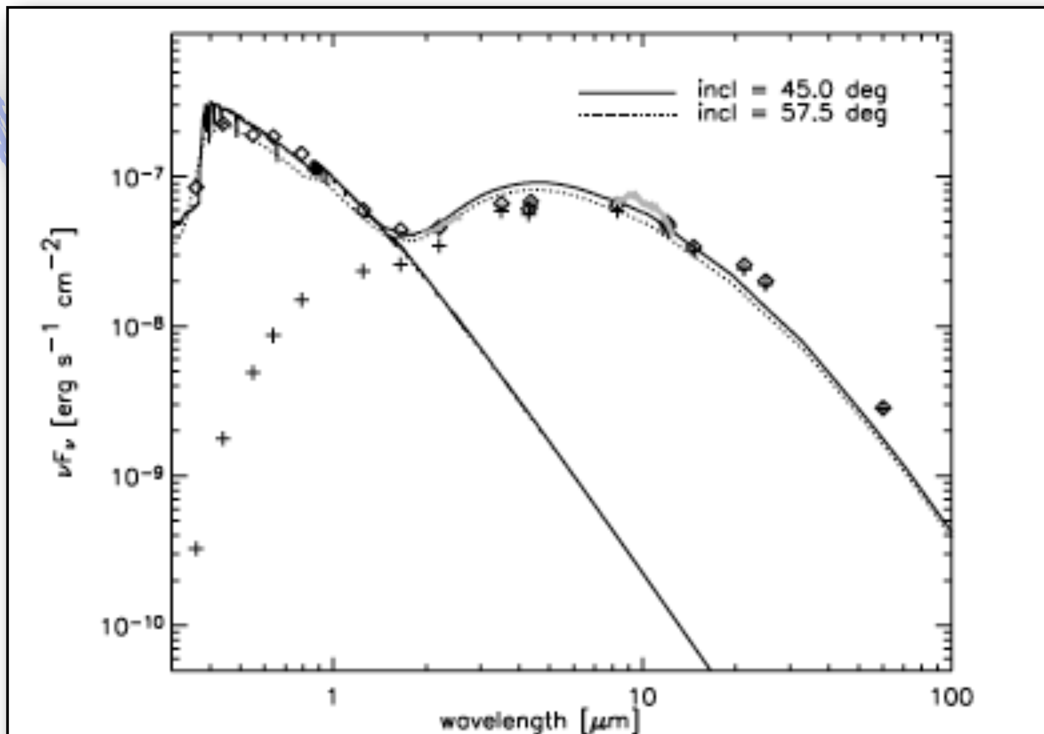
AMBER and MIDI interferometric observations of the post-AGB binary IRAS 08544-4431: the circumbinary disc resolved★

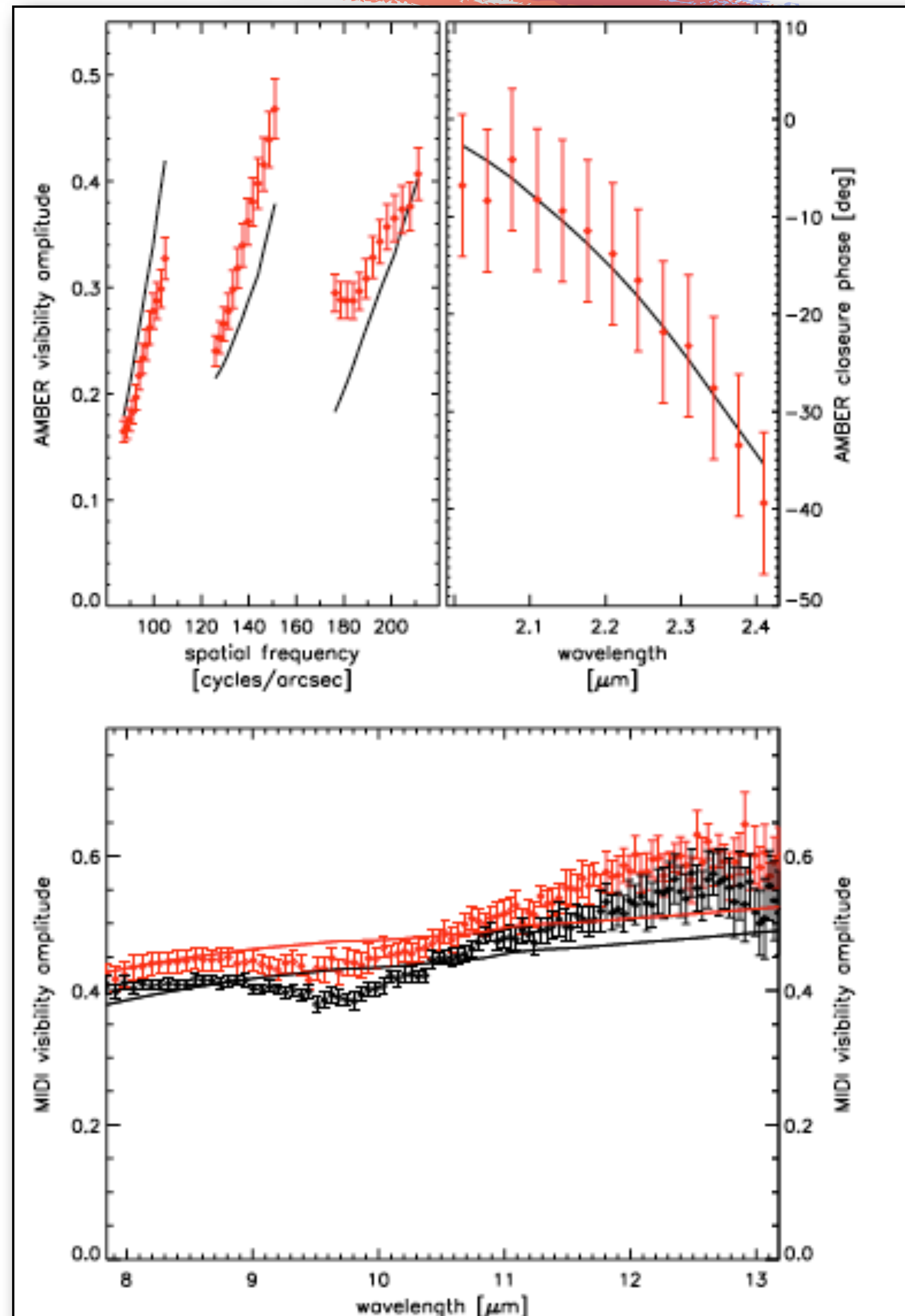
P. Deroo[1], B. Acke[1,★★], T. Verhoelst[1,★★], C. Dominik[2], E. Tatulli[3], and H. Van Winckel[1]



A&A 474, L45–L48 (2007)

Circumstellar dust: (stable?) disks: Post-AGB



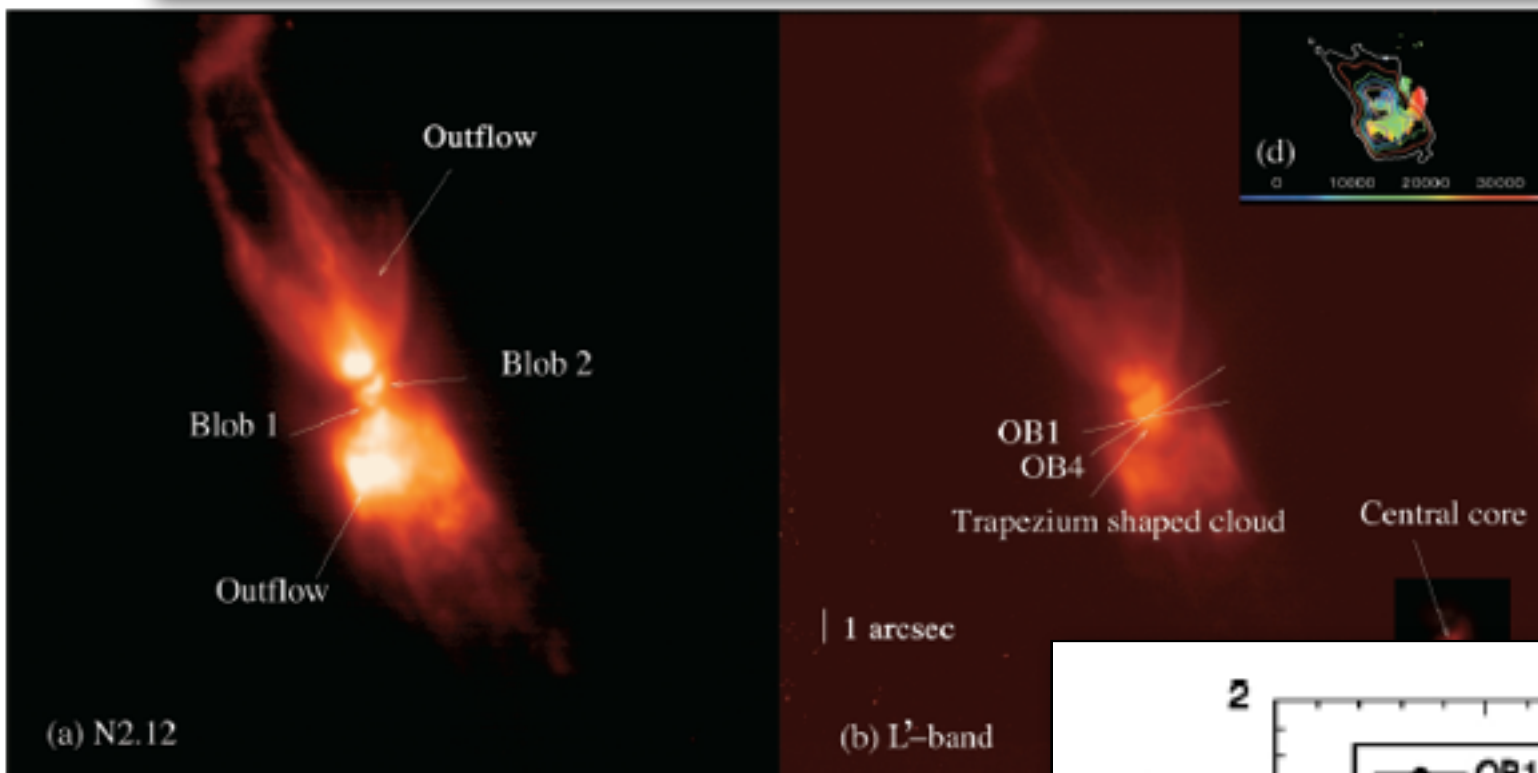


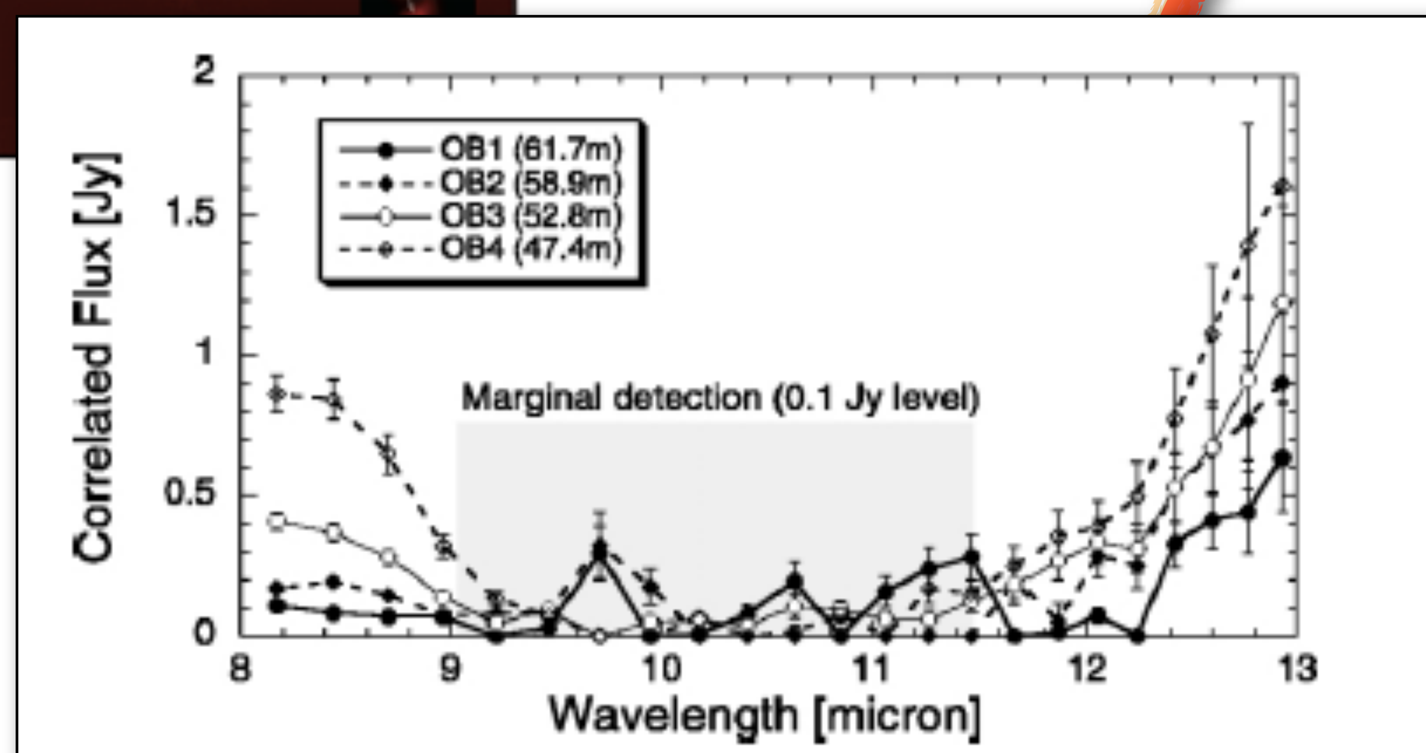
Circumstellar dust disks: (Proto-) Planetary Nebulae

THE COMPACT CIRCUMSTELLAR MATERIAL AROUND OH 231.8+4.2[1]

M. Matsuura,[2,3,4] O. Chesneau,[5] A. A. Zijlstra,[2] W. Jaffe,[6] L. B. F. M. Waters,[7,8] J. A. Yates,[9] E. Lagadec,[2] T. Gledhill,[10] S. Etoka,[2] and A. M. S. Richards[11]

Received 2006 April 28; accepted 2006 June 21; published 2006 July 24





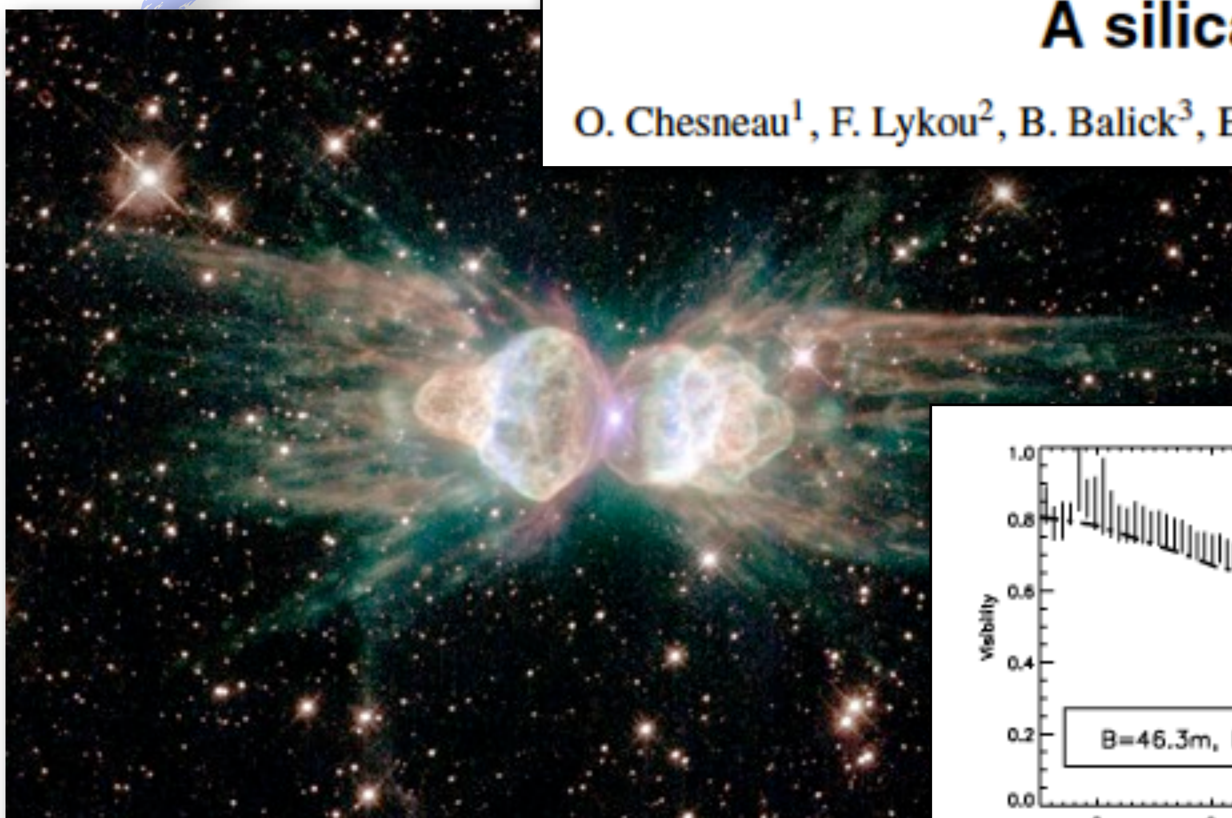
The Astrophysical Journal, 646:L123–L126, 2006

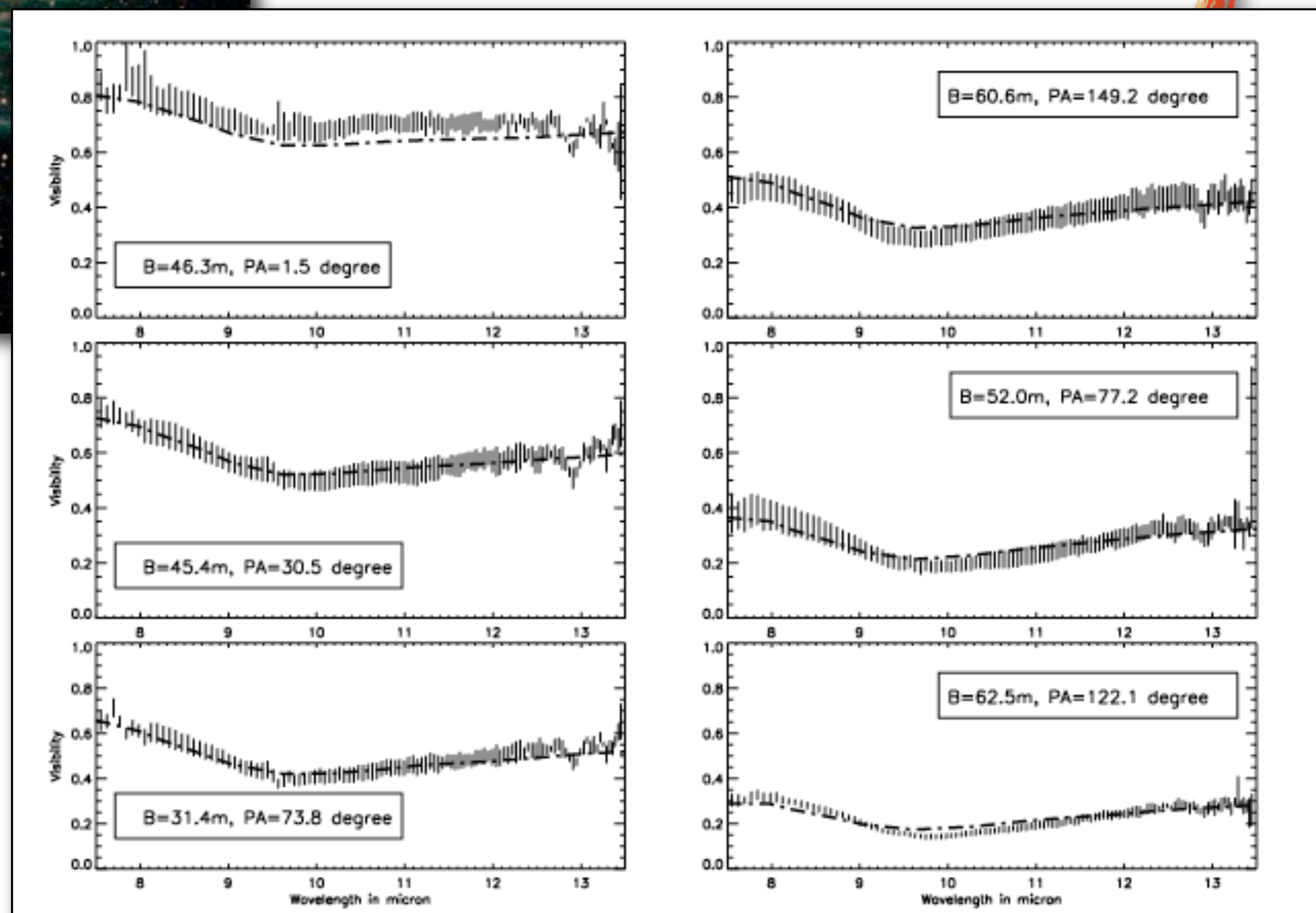
Circumstellar dust disks: (Proto-) Planetary Nebulae

Letter to the Editor

A silicate disk in the heart of the Ant

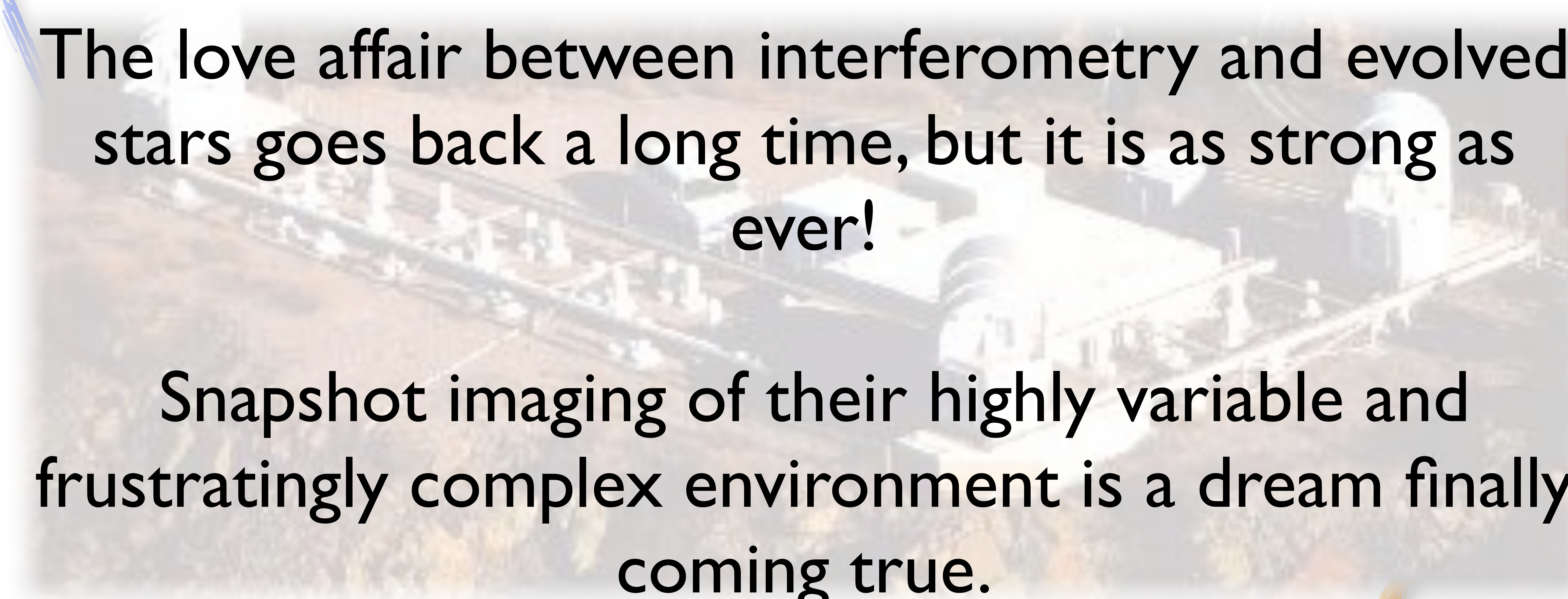
O. Chesneau[1], F. Lykou[2], B. Balick[3], E. Lagadec[2], M. Matsuura[4], N. Smith[5], A. Spang[1], S. Wolf[6], and A. A. Zijlstra[2,⋆]





A&A 473, L29–L32 (2007)

Conclusions



The love affair between interferometry and evolved stars goes back a long time, but it is as strong as ever!

Snapshot imaging of their highly variable and frustratingly complex environment is a dream finally coming true.