INTERFEROMETRIC OBSERVATIONS OF EVOLVED STARS

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“Ten years of VLTI” conference, ESO Garching
25 October 2011

Outline

- **Motivation**
- **Modeling**
  - Modeling – Theory
  - Modeling – Simulations
- **Observations**
  - Monitoring of photometry and visibility variations as a function of phase and cycle
  - Modeling results
- **Comparison of MIDI Observations and Simulations for RR AQL, S ORI, GX MON, and R CNC**
- **Conclusions**
- **Outlook**

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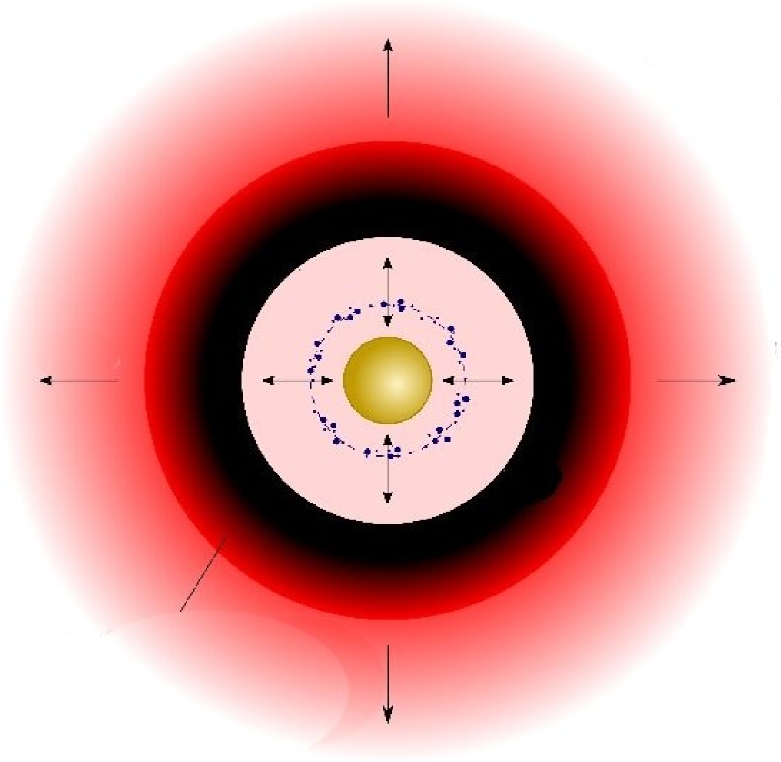
-> to better understand the mass loss process

AGB stars create > 50% of the dust

~80% of all stars evolve through AGB

- **Investigation:**
  - **pulsation mechanism**
  - **dust condensation sequence**
- **high angular resolution**
- **wavelengths**
  - **near-infrared**
  - **mid-infrared**



credit: ESO

- **the best currently available modeling approach**

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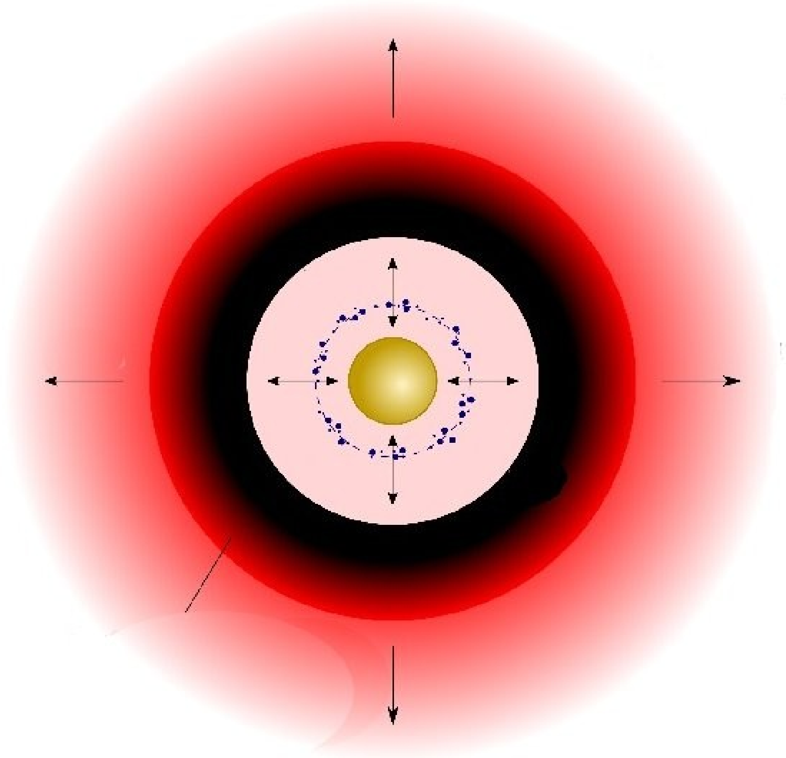

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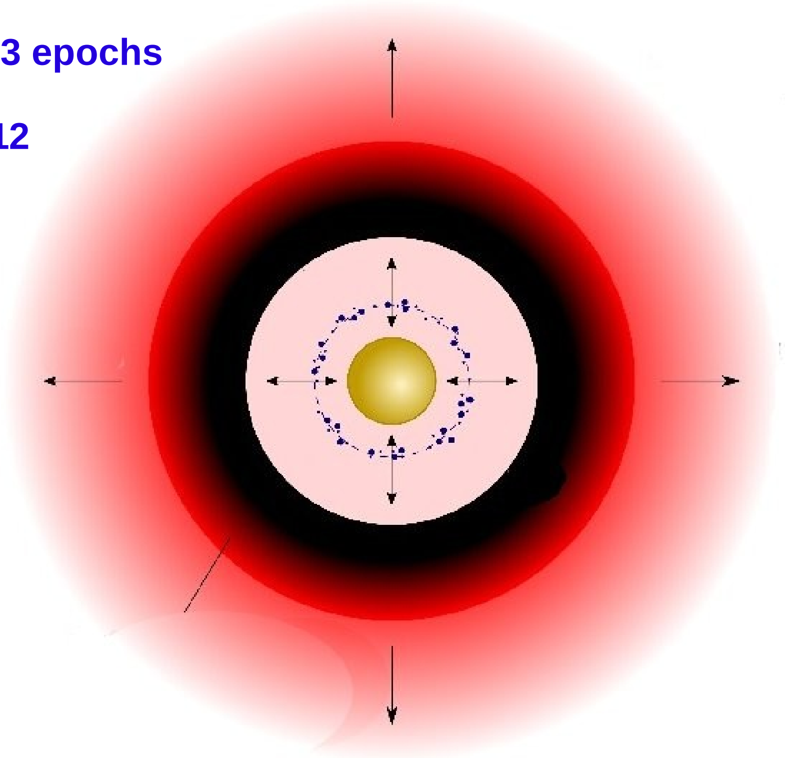

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AGB Stars – Introduction

Dust condensation sequence ?

multi-component mixture

- **Silicate Condensates**
  - 9.7 and 18 μm

- **Aluminium Oxide Al_2O_3**
  - broad emission feature
  - 11.5-11.8 μm or 13 μm
  - The first solid that condensate in the outflow
  - a seed nuclei

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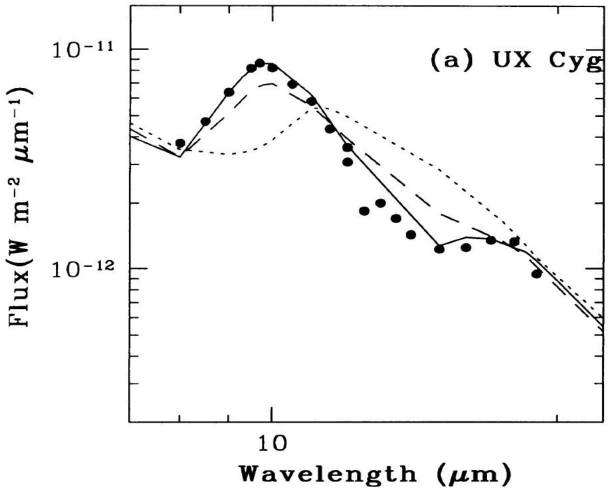

Lorenz-Martins & Pompeia, 2000

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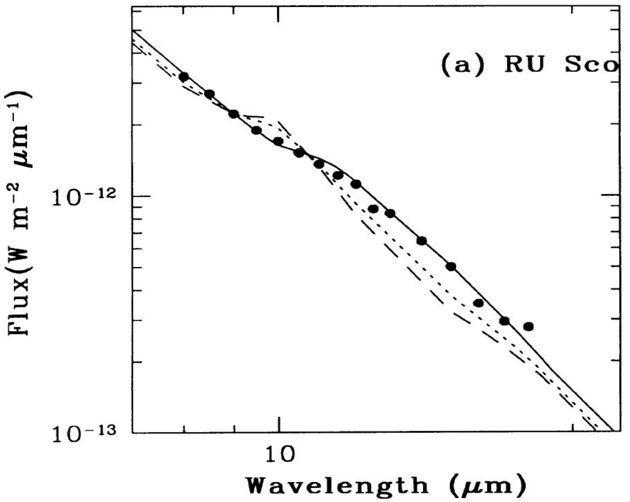

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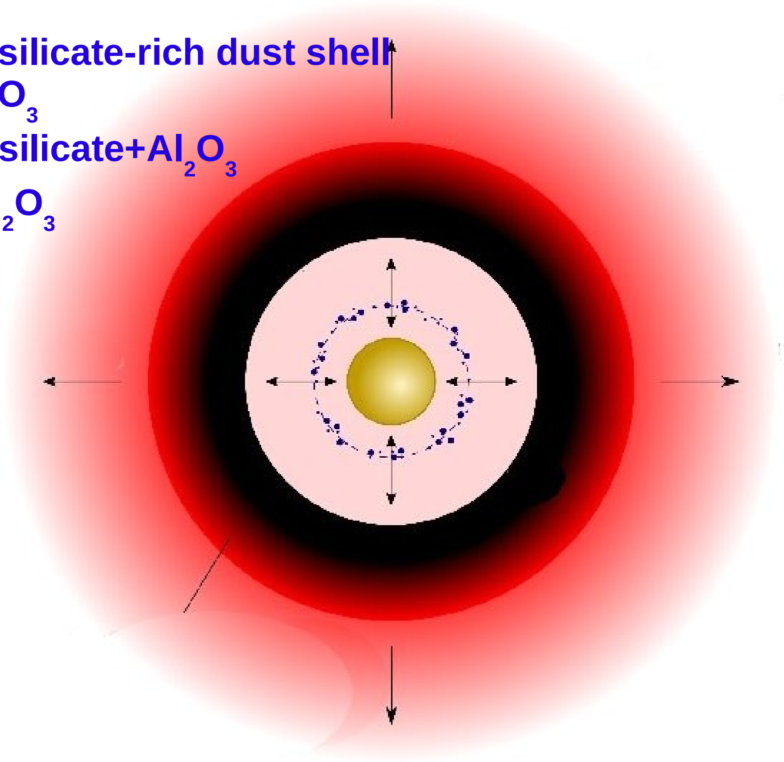
RR AQL – silicate-rich dust shell
S ORI - Al_2O_3
GX MON - silicate+Al_2O_3
R CNC - Al_2O_3



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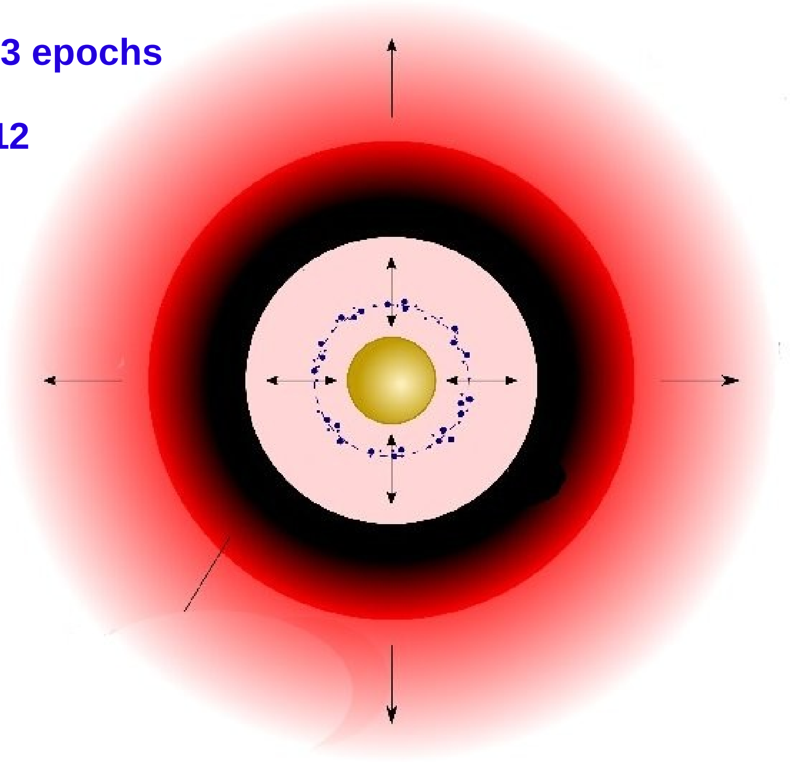

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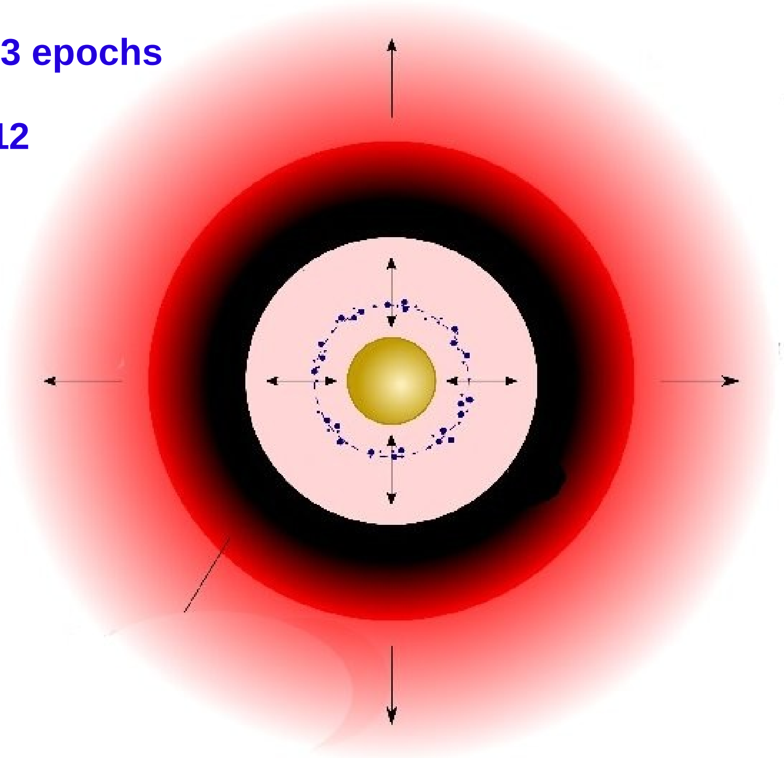

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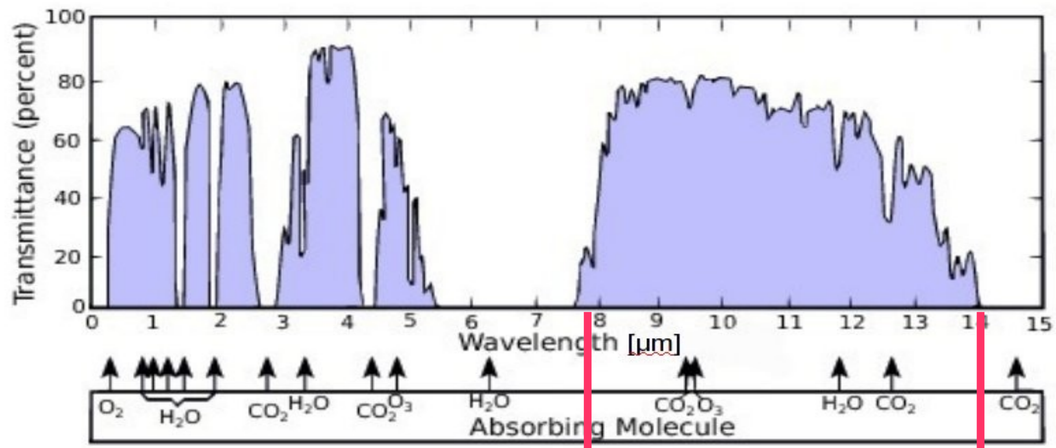
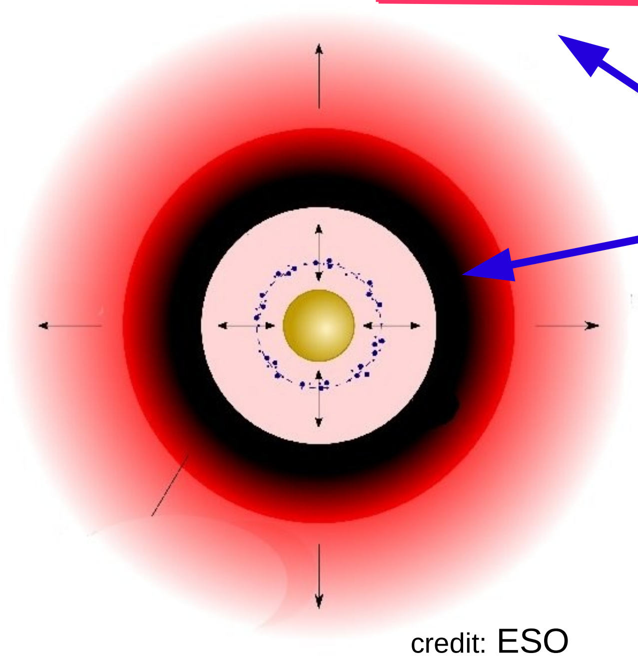


credit: U.S. Navy



MIDI
mid-infrared

- dust formation zone
- inner circumstellar dust shell
- chemical composition

credit: ESO

The MID-infrared Interferometer Instrument (MIDI) at the VLTI

credit: ESO

- combines **two beams**
  in the pupil plane (Michelson recombiner)
- **N-band 7 -13 µm**

- **ATs**
- **Uts**

- **HIGH SENS mode** (high sensitivity)
- **SCI PHOT mode** (high precision)

- The instrument provides **spectral resolution**
  R = 30 (dispersive element **PRISM**) or
  R = 230 (**GRISM)**

- **MIDI data reduction**

  - **EWS the Expert Work Station** (by Walter Jaffe)
  - **MIA MIDI Interactive Analysis** (by Rainer Köhler)

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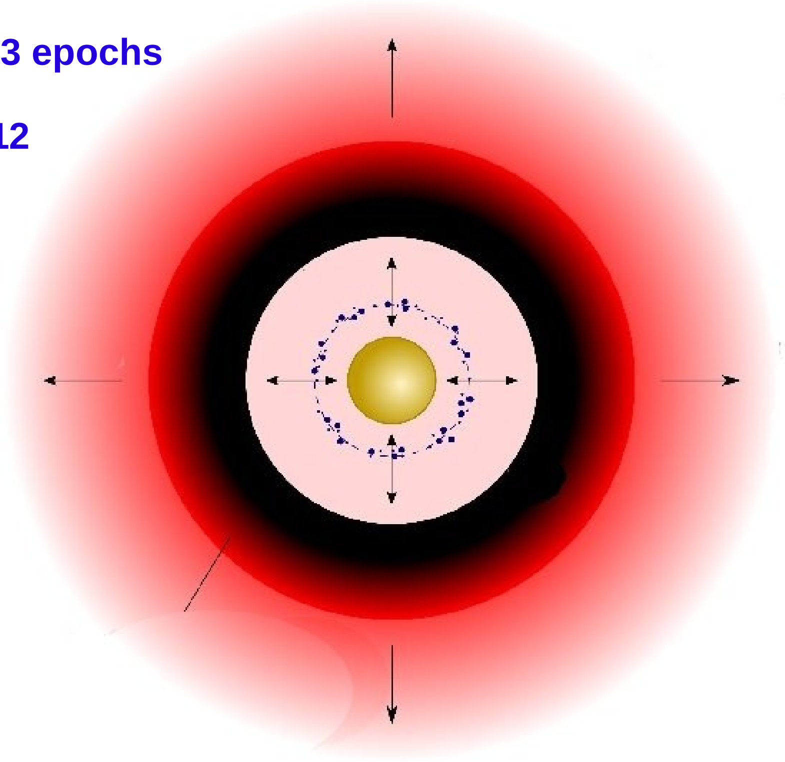

- **high angular resolution** → **VLTI**

- **wavelengths**
  - **near-infrared**
  - **mid-infrared** → **MIDI**
    (atmospheric windows, emitting star and dust, +silicate feature)

- **the best currently available modeling approach for oxygen-rich AGB stars**

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Modeling of the MID-INFRARED interferometric data

- **Uniform disk**

- **Gaussian distribution**

- ***ad-hoc* radiative transfer model -** Monte Carlo radiative transfer code mcsim_mpi
  (Ohnaka et al.2006)

- ***dust-free dynamic model atmosphere series***
  (Hofmann et al 1998, Bessell et al. 1996, Ireland et al. 2004a,b)

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  *dynamic model atmosphere **- Central star***

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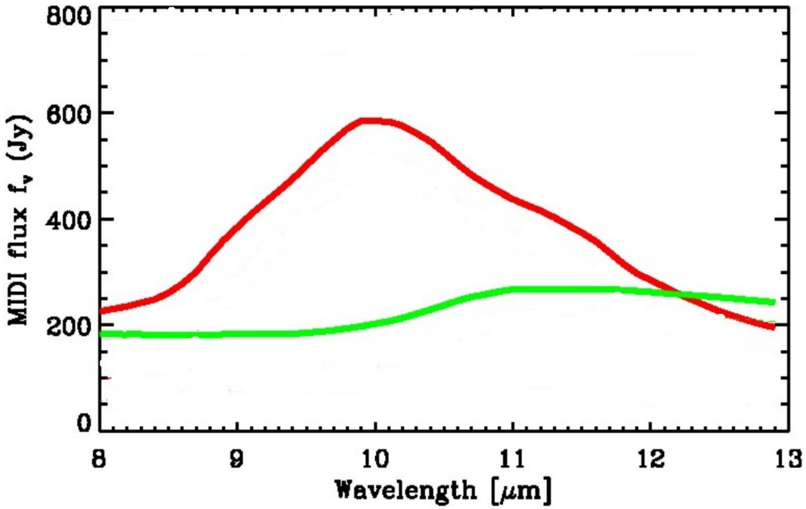
Modeling of the visibility and photometry variations in the mid-infrared

? **expected variations with phase**

? **optimal Bp**

? **optical depth**

? **dust formation**

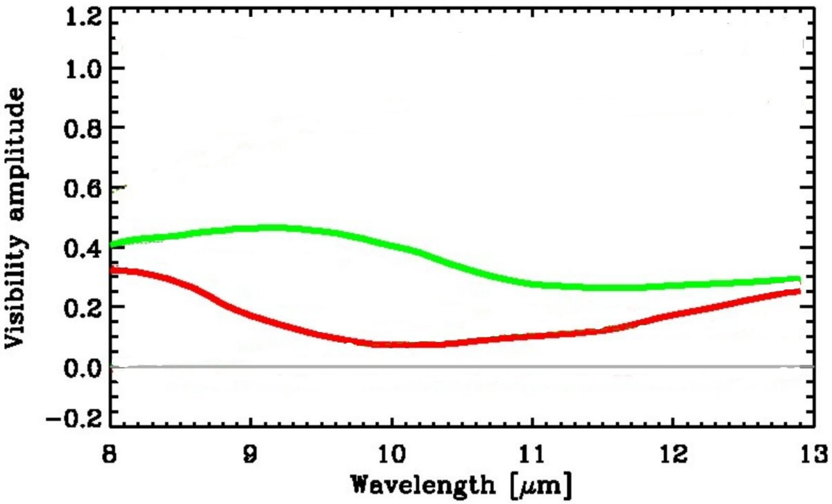


3 groups of simulations of atmosphere composed of :
(Lorenz-Martins & Pompeia 2000)

I. - silicate-rich dust shell (RR AQL)

II. - Al_2O_3-rich dust shell (S ORI)

III. - Al_2O_3 + silicate-rich dust shell (GX MON)



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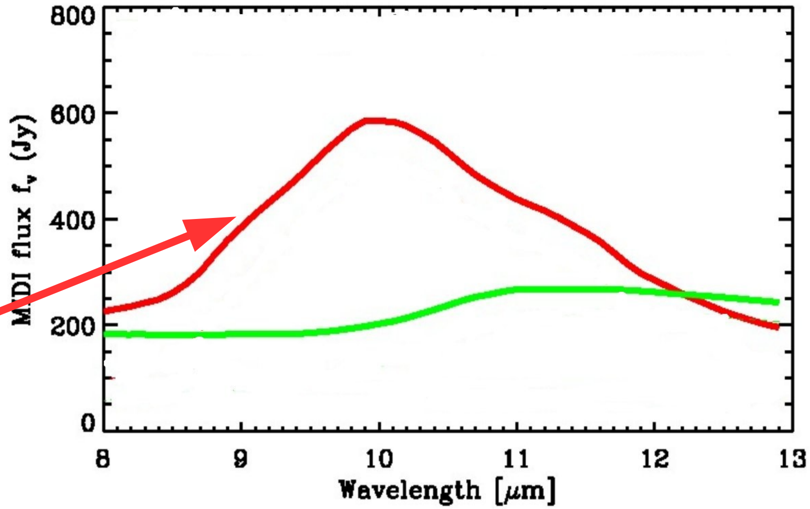

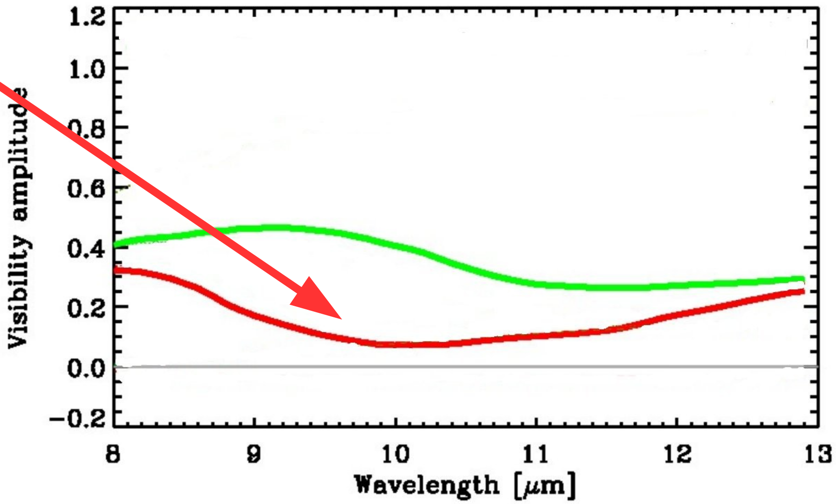

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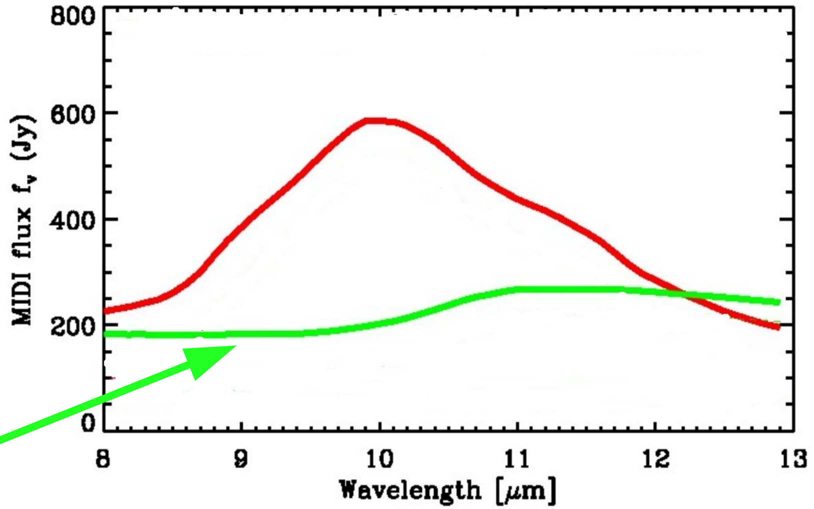

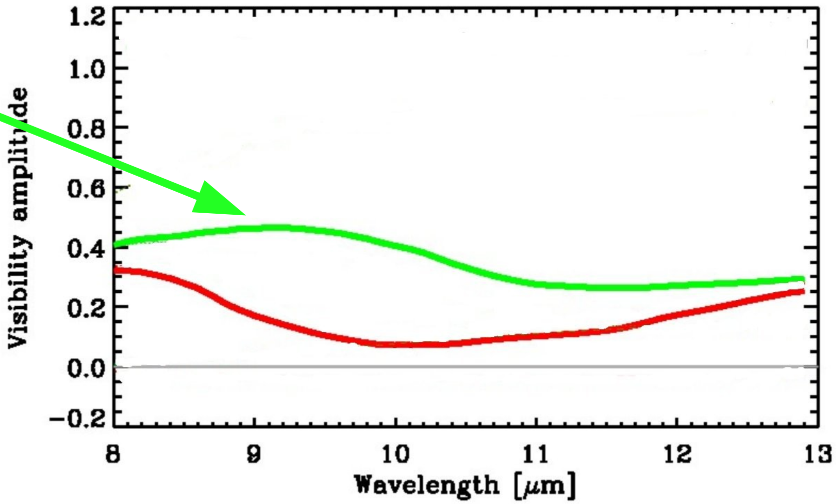

Simulations of the visibility and photometry variations in the mid-infrared

Model	cycle+Φ	L/L⊙	T_{eff} (K)
M16n	1+0.60	2460	2860
M18	1+0.75	4840	3310
M18n	1+0.84	4980	3020
M19n	1+0.90	5070	2900
M20	2+0.05	4550	2650
M21n	2+0.10	4120	2550
M22	2+0.25	2850	2330
M23n	2+0.30	2350	2230
M24n	2+0.40	1540	2160
M25n	2+0.50	2250	2770

M series
P = 332 days
M/M⊙ = 1.2

+ 6 dust shell parameters

- **Optical depth** (at wavelength 0.55 μm)
  - Al_2O_3 for λ < 8 μm (Koike et al.1995), for λ > 8 μm (Begemann et al.1997)
  - silicates (Ossenkopf et al.1992)
- **Inner boundary radii**
- **The power law index of the density distribution**

- **The continuum photospheric diameter**
- **Projected baseline length**

RESULTS

	RR AQL 13 epochs	S ORI 14 epochs	GX MON 12 epochs	R CNC 2 epochs
Intra-cycle cycle-to-cycle vis variations	**X** uncertainties 5-20%	**X** uncertainties 5-20%	**X** uncertainties 5-20%	----
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Phase coverage	0.45-0.85	0.90-1.20	**?**	~0.03
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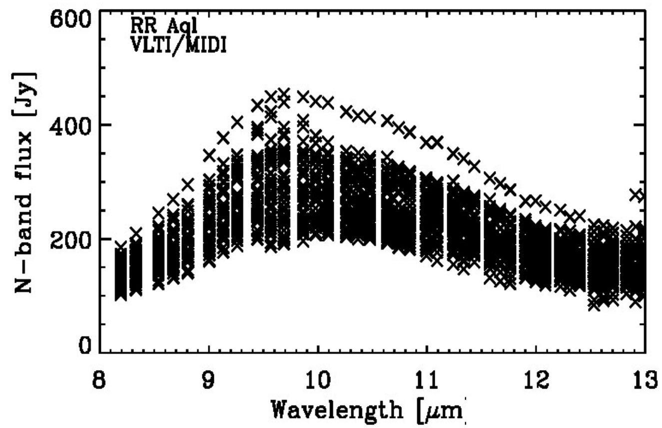
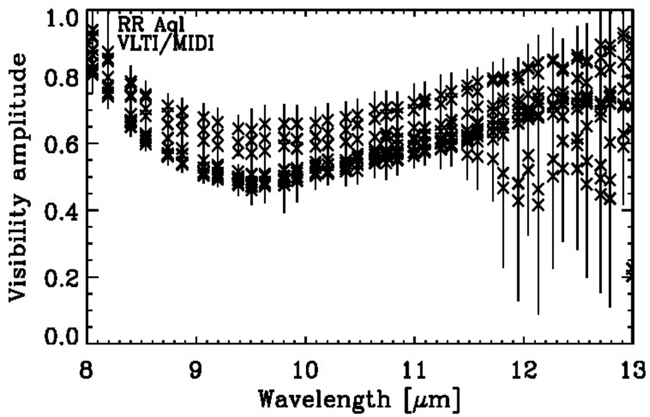
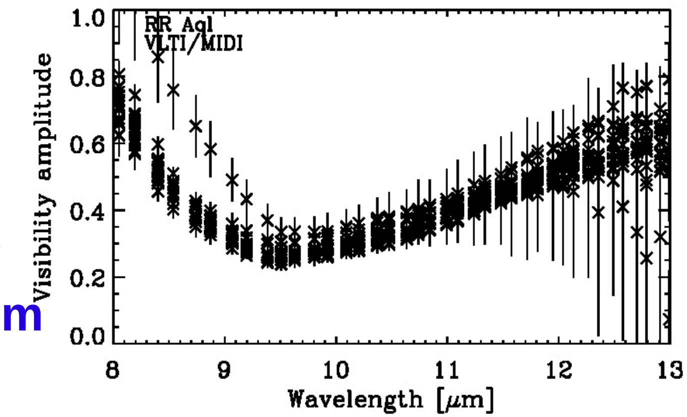
MULTIEPOCH INFRARED INTERFEROMETRIC OBSERVATIONS OF EVOLVED STARS AT THE VLTI
MIDI Observations of RR AQL
Silicate-rich dust shell

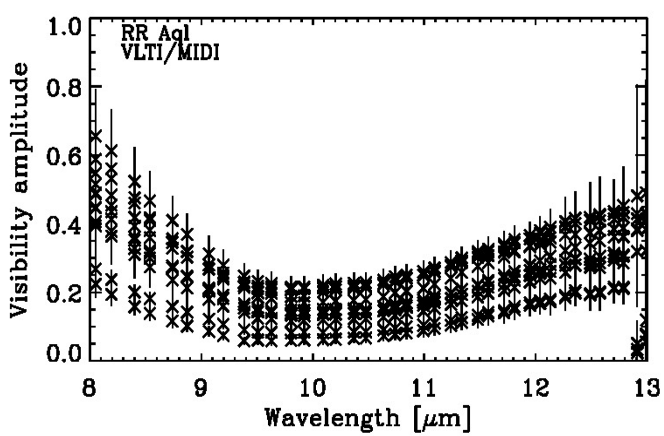




Bp < 20m

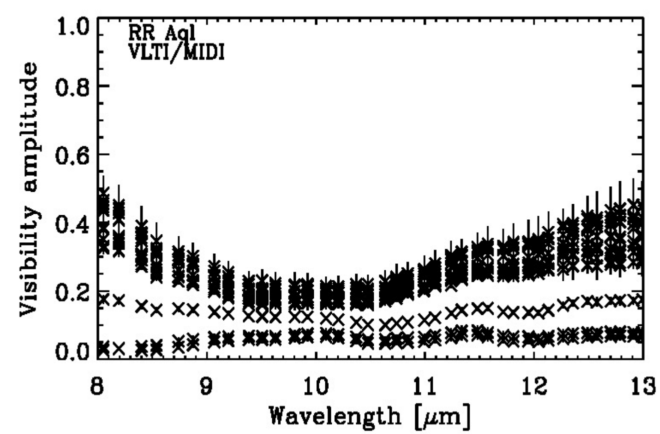
20m < Bp < 35m





35m < Bp < 50m

Bp > 50m



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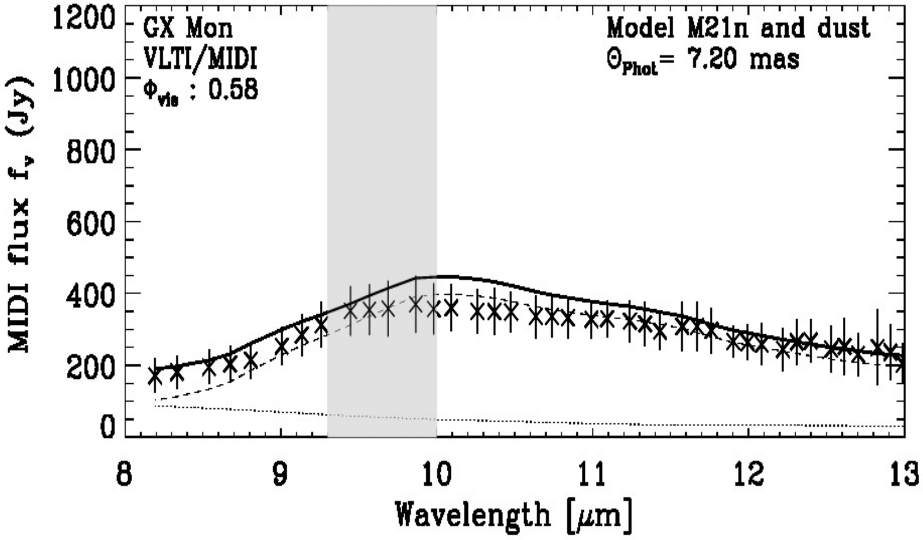
Results – model fitting

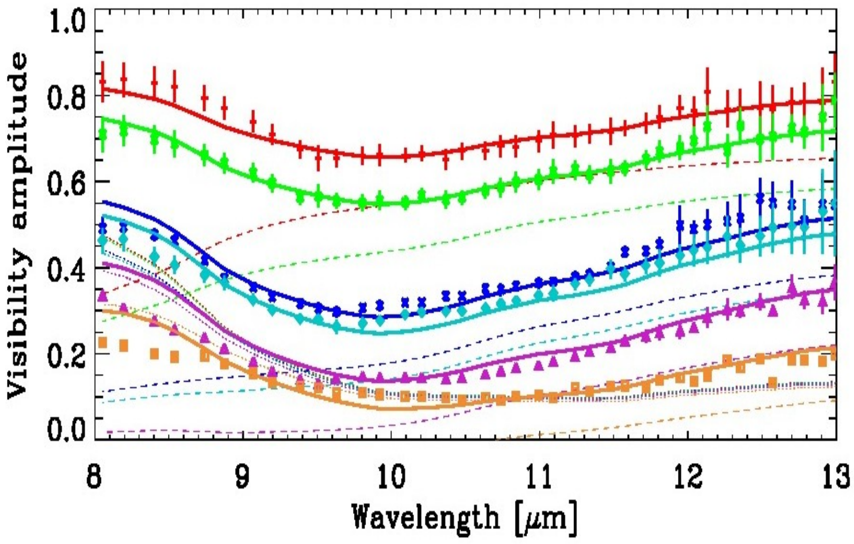
GX MON

Al_2O_3 + silicate dust shell

Epoch E



(a)



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Conclusions

- **Mass-loss rates** adopted from the literature

-> dust condensation sequence ?

star	dust shell	M⊙/year
R CNC	Al_2O_3 grains	$0.2\ 10^{-7}$
S ORI	Al_2O_3 grains	$2.2\ 10^{-7}$
GX MON	Al_2O_3 + silicate grains	$5.4\ 10^{-7}$
RR AQL	silicate grains	$9.1\ 10^{-7}$

- **low mass-loss rates** - **Al_2O_3 grains**
- **high mass-loss rate – silicates**

+ Little-Marenin & Little (1990) and Blommaert et al. (2006)

x Sloan & Price (1998)

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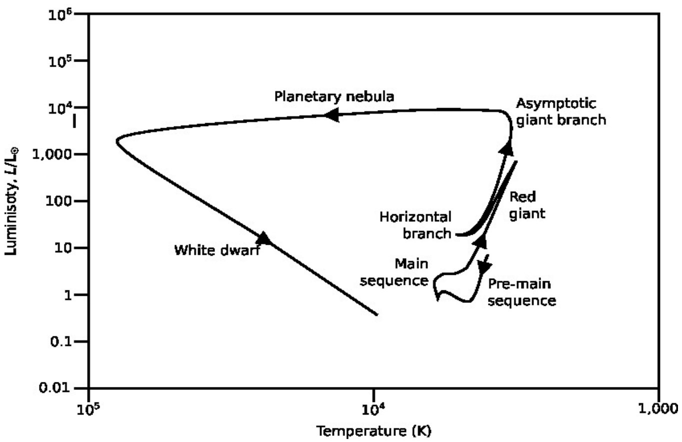

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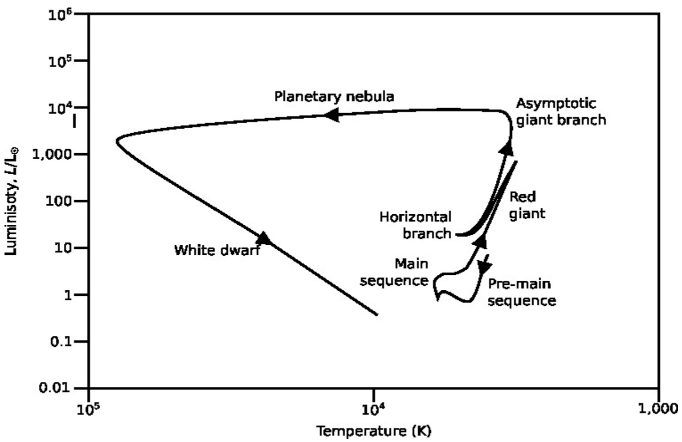
R CNC	Al_2O_3 grains	$0.2\ 10^{-7}$
S ORI	Al_2O_3 grains	$2.2\ 10^{-7}$
GX MON	Al_2O_3 + silicate grains	$5.4\ 10^{-7}$
RR AQL	silicate grains	$9.1\ 10^{-7}$

along AGB

- **low mass-loss rates - Al_2O_3 grains**
- **high mass-loss rate – silicates**



+ Little-Marenin & Little (1990) and Blommaert et al. (2006)

x Sloan & Price (1998)

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  - many different Bp and P.A.
  - Investigations of the circumstellar dust shell and characteristics of the atmosphere
  - **No evidence of intra-cycle and cycle-to-cycle visibility variations**
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  - the best approach currently available
    -> the photometric and visibility spectra can be well described

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  - Wittkowski et al. (2007) MIDI data **– dust shell, model parameters**
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  - Little-Marenin & Little (1990) and Blommaert et al. (2006) **– dust condensation sequence**

Outlook

- **Further infrared interferometric observations using MIDI & AMBER at the VLTI**
- **Image reconstruction**
- **Further analysis of the RR Aql data (VLTI / AMBER)**
- **Radio interferometric observations at the VLBA**
- **Comparison with multi-epoch observations of carbon-rich stars**
- **Comparison with multi-epoch observations of red supergiants**
- **Future high resolution facilities**
  - **MATISSE**