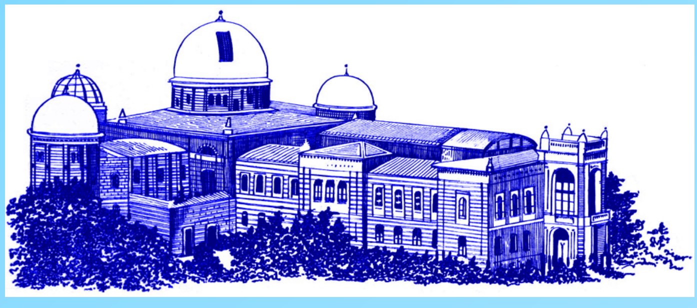
Observing and modeling the dynamic atmosphere of the low mass-loss C-star R Sculptoris at High Angular Resolution



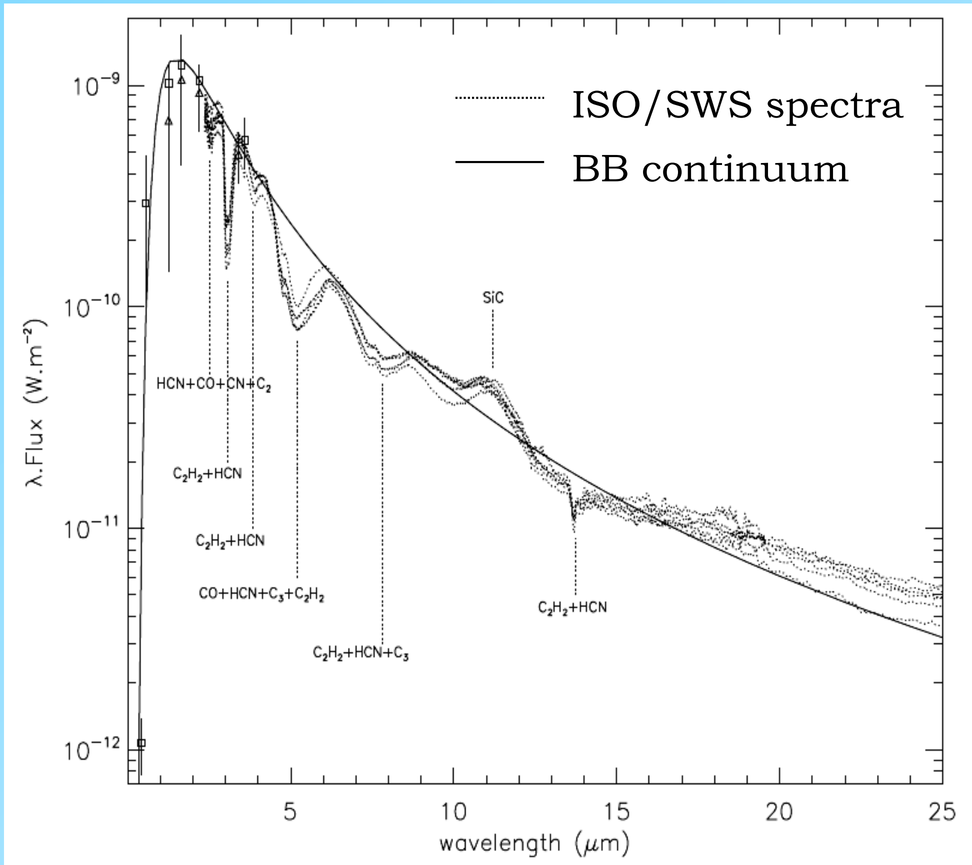
Stéphane Sacuto,
Institut für Astronomie der Universität Wien

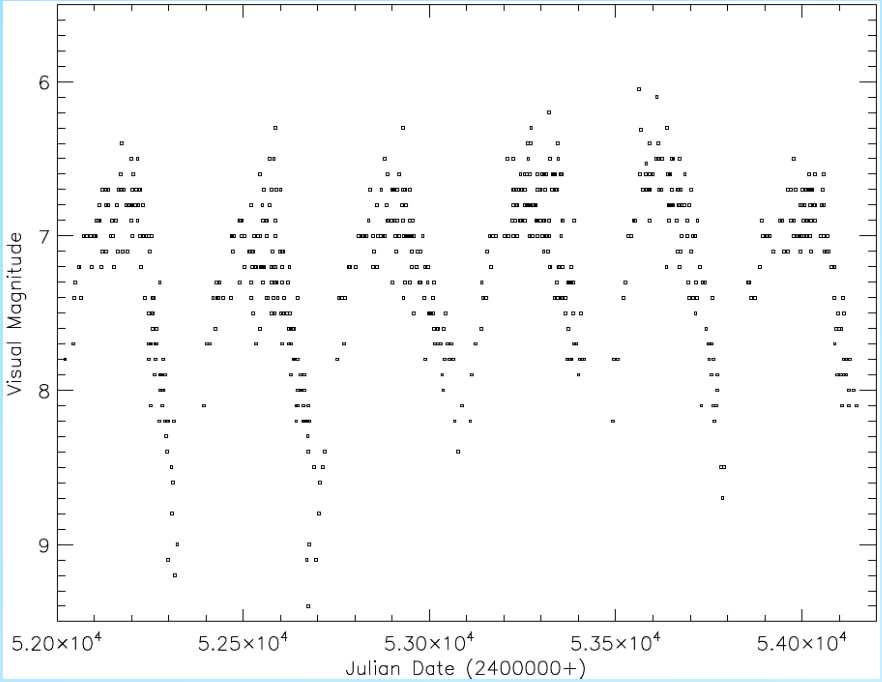
04 March 2010, ESO Garching

Col. Aringer B., Hron J., Nowotny W., Paladini C., Verhoelst T., and Höfner S.

The carbon rich star R Sculptoris

Characteristics	Period	Distance	Mass-loss
SrA / V=7.4±0.7/ 145 Jy @ 10μm	374 days	470 pc (Hip) / 360 pc (P-L)	1 to 5×10^{-7} $M_{\odot}yr^{-1}$





(AAVSO)

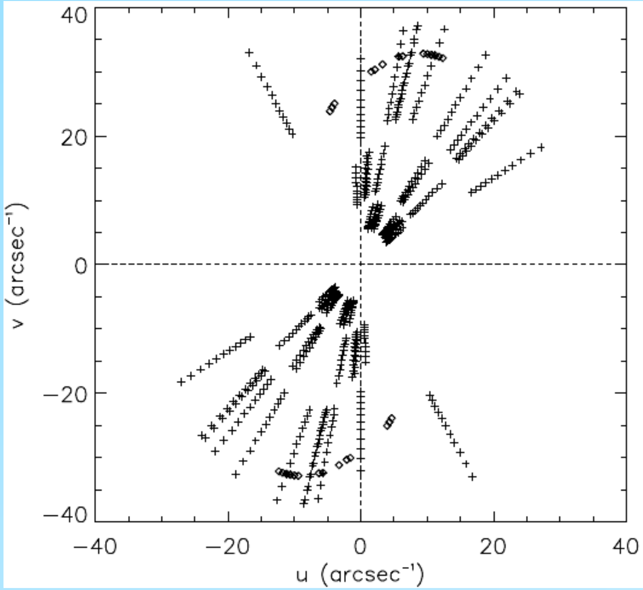
Spectro Interferometric measurements

VINCI (2.0-2.4µm)

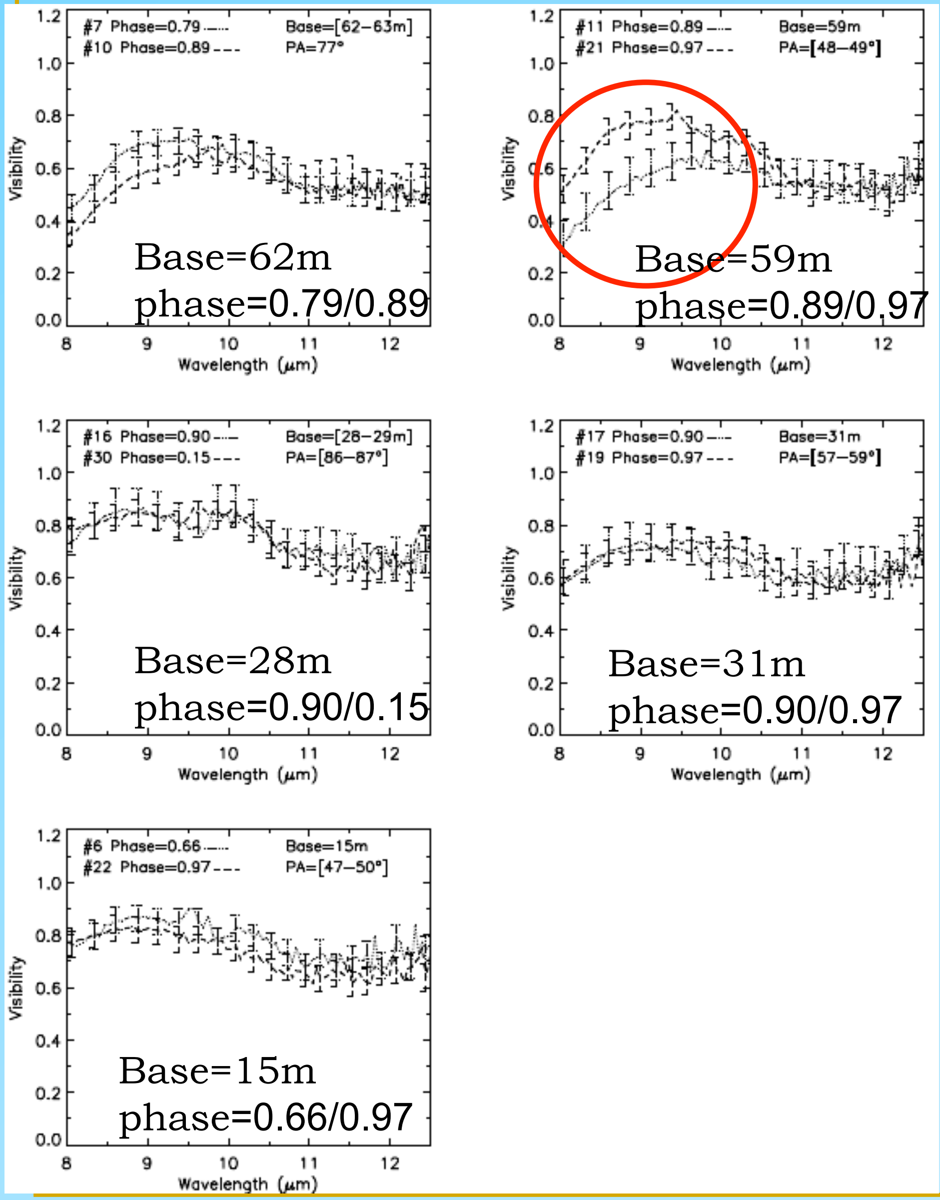
- November/December 2001
- Phases: 0.17/0.23
- Config. E0-G0
- Bases = 11-16 m
- PA = 69-101°
- Broadband

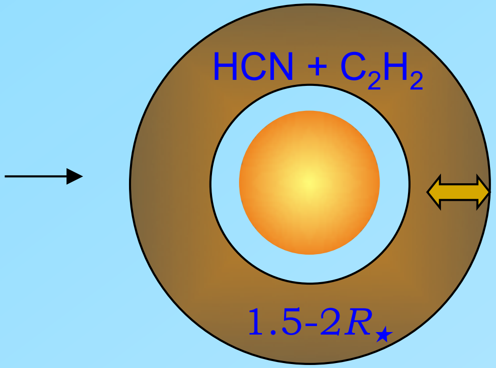
MIDI (8-13µm)

- January 2005 and June-December 2006
- Phases: 0.14/0.23/0.65/0.79/0.90/0.98
- Config. E0-G0, D0-G0, A0-G0, G0-K0, G0-H0, and D0-H0
- Bases = 11-64 m
- PA = 34-117°
- Spectrally dispersed from 8 to 13µm

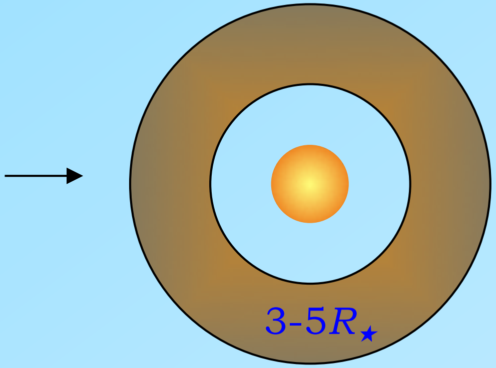


Interferometric variability in the Mid-IR

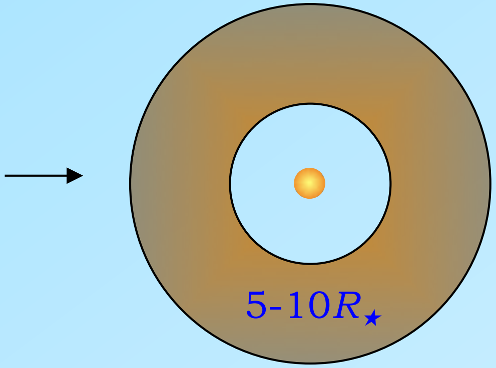




Significant variations close to Max. Brightness



No significant variation



No significant variation

The Dynamic Model Atmosphere (DMA)

❑ Treatment

Höfner et al., 2003

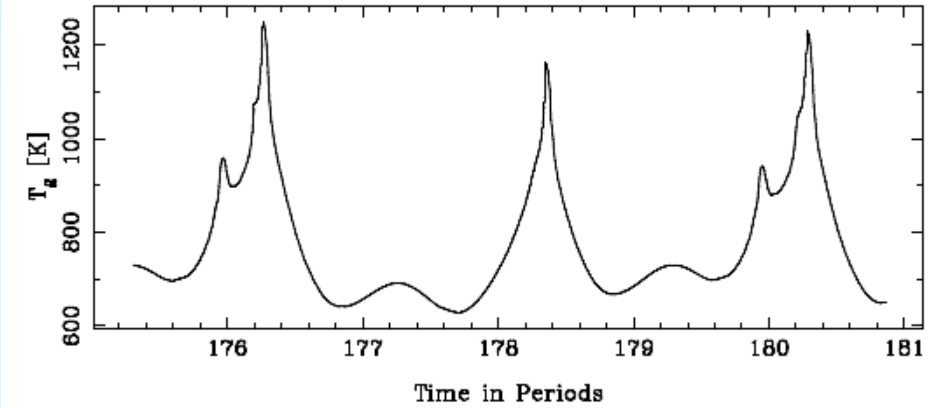
Components	**Numerical treatment**
Initial hydrostatic structure (L;M;T_{eff};Z;C/O)	temperature-density structure(T=0)
Radiation (photons) + Gas and dust(AmC)	Hydrodynamic + radiative transfer(Sph Sym.) + Dust formation, increase, and evaporation **temperature-density structure(T)**
Opacities (COMA code; *Aringer 2000*)	Radiative transfer (spherical symmetry) Intensity distribution, spectra, visibilities

❑ Simulation of the pulsation

Sinusoidal motion of the inner boundary « piston effect »

❑ Results

- **Temperature**
- **Density**
- **Degree of condensation**
- **Mass-loss rate**
- **I(r,l) ; F(λ) ; V(B/l,l) ; …**



Modeling the dynamic atmosphere of R Scl

Step 1: Hydrostatic modeling of the stellar atmosphere to determine the initial hydrostatic structure of the DMA.

Step 2: Since only AmC dust is treated in the hydrodynamic calculation, opacities of SiC dust (SED) are added in the COMA a posteriori radiative transfer computation.

Step 3: The DMA of R Scl is chosen based on the parameters deduced from the best hydrostatic fit of the stellar atmosphere together with the SiC dust parameters.

Step 1: hydrostatic modeling of R Scl

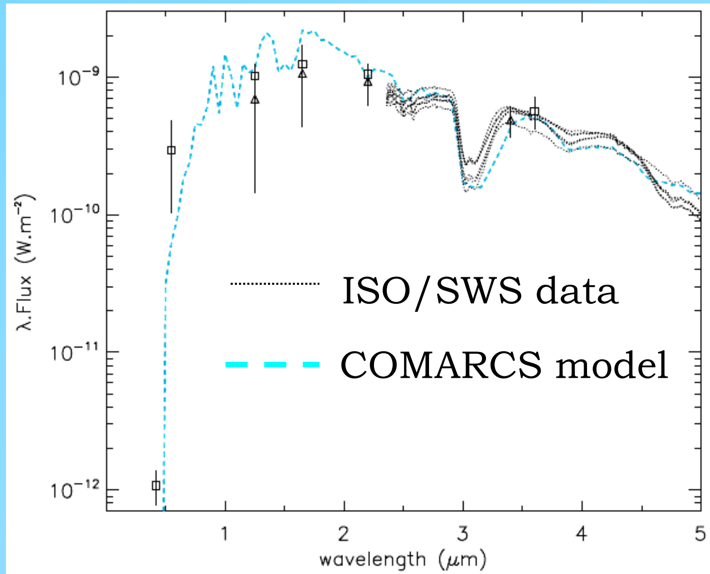
Use of the **COMARCS models** (Aringer et al. 2009)

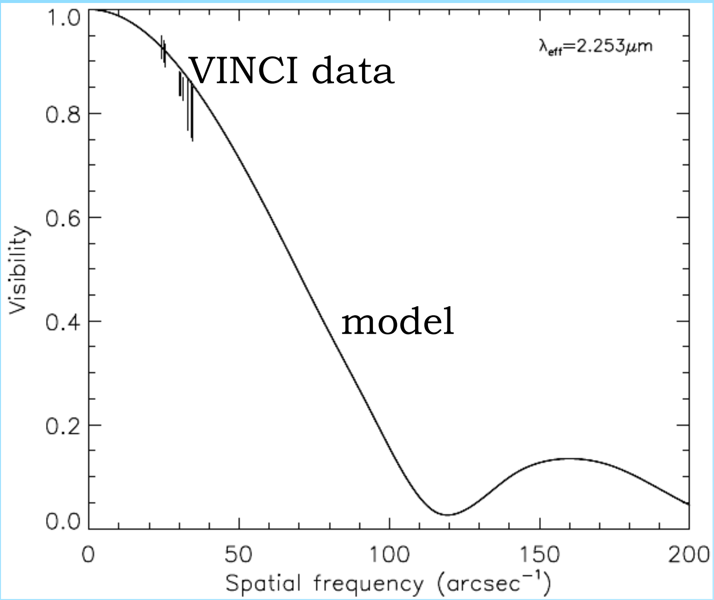
- 1D models (spherically symmetric)
- Hydrostatic and chemical equilibrium, LTE
- Atomic and molecular opacities are calculated for a given temperature and density

Fitting procedure :

- Fit of the [2.4-5μm] ISO/SWS spectral features, the NIR photometric and interferometric measurements
- Least-square fitting minimization from a grid of COMARCS models varying: T_{eff} ; L ; D ; M ; Z ; C/O

Result





Parameter	Value
Effective temperature	**2700 K**
Luminosity	**7000 $L_\odot$**
Distance	**350 pc**
Star diameter	**10.2 mas**
Surface gravity (log *g*)	**-0.7**
Micro-turbulent velocity	**2.5 km/s**
Stellar mass	**1 $M_\odot$**
Metallicity	**1 $Z_\odot$**
C/O	**1.4**

Step 2: Inclusion of a dusty environment

Use of the **DUSTY models** (Ivezic et al. 1999)

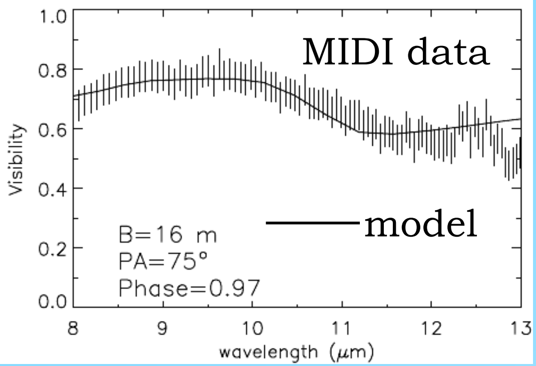
- 1D models (spherically symmetric)
- Solve the radiative equation in a dusty environment
- Integrate different type of astronomical dust
- Use of the best fitting COMARCS model as central source
- Compute the wind structure to derive a mass-loss rate

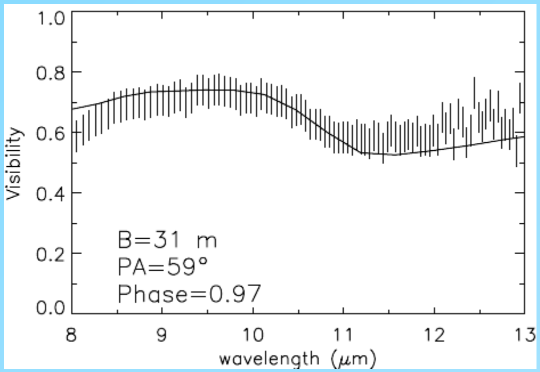
<u>Fitting procedure :</u>

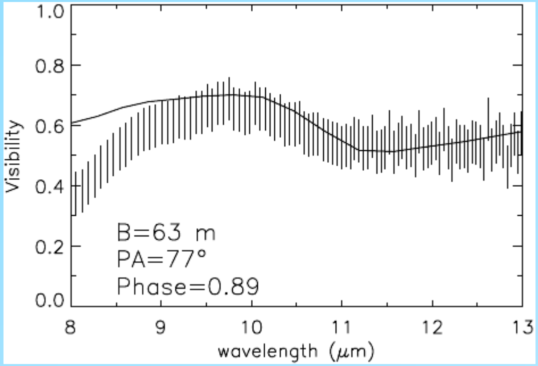
- Fit of the [2.4-25µm] ISO/SWS measurements, the Near-IR photometric and interferometric, and Mid-IR spectro-interferometric measurements

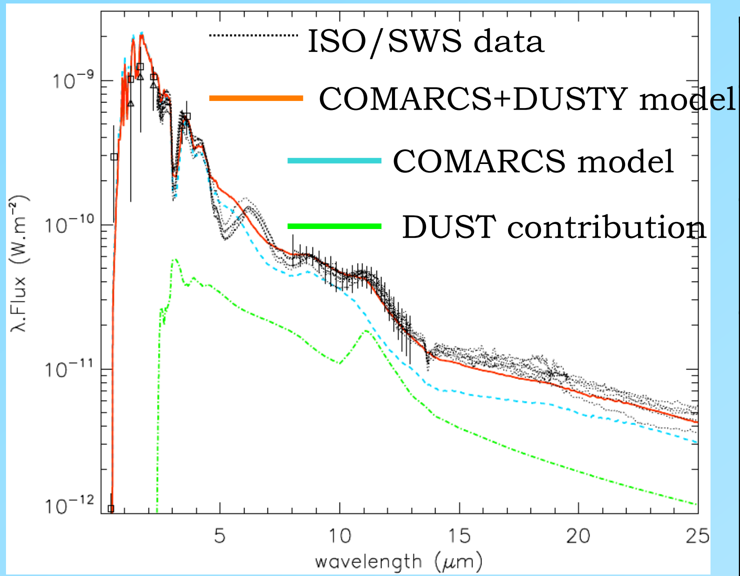
- Least-square fitting minimization from a grid of DUSTY models varying: (n,k) ; AmC/SiC ; $t_{0.55\mu m}$; T_{in}

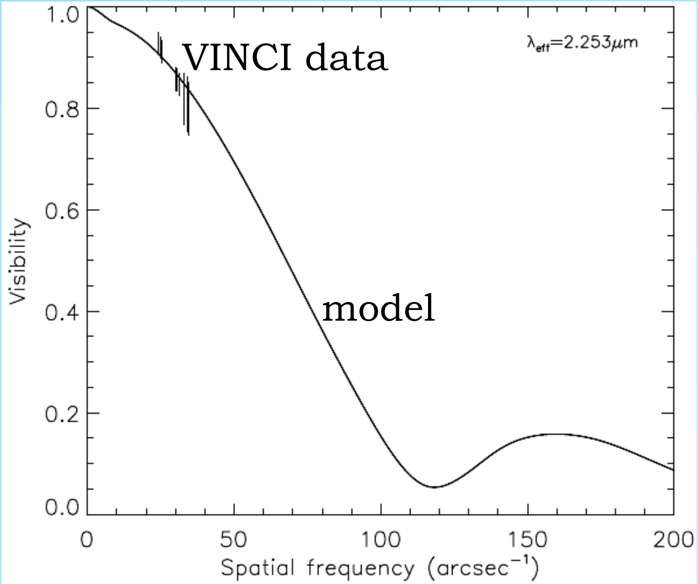
Result





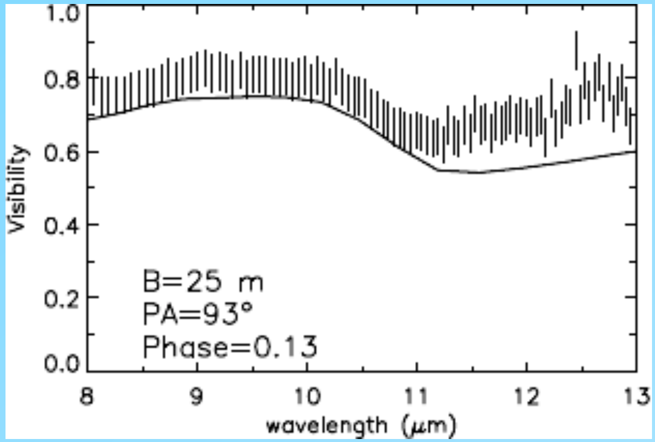


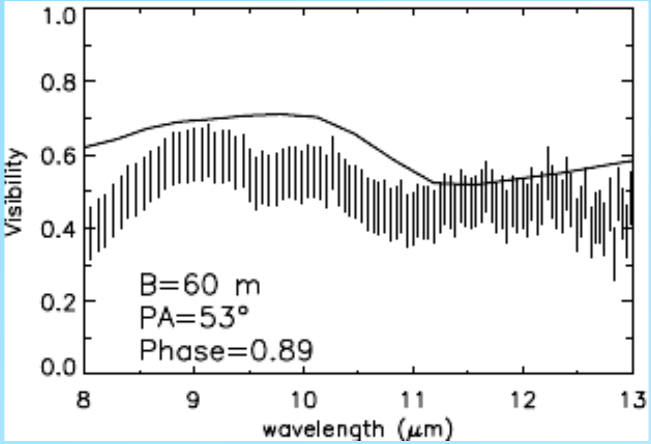




Parameter	Value
Inner shell radius	**22.4 mas**
Inner shell temperature	**1200 K**
Grains abundance and chemistry	**90% AmC (Rouleau) + 10% SiC (Pégourié)**
Grain size distribution	**$a^{-3.5}$ (MRN)**
Geometrical thickness	**2.2”**
$t_{0.55\mu m}$	**0.4**
$t_{11.3\mu m}$	**7.6E-3**
Mass loss rate	**(6.7±2)E-7** $M_{\odot}/yr$

Disagreement between the DUSTY+COMARCS model and the observations



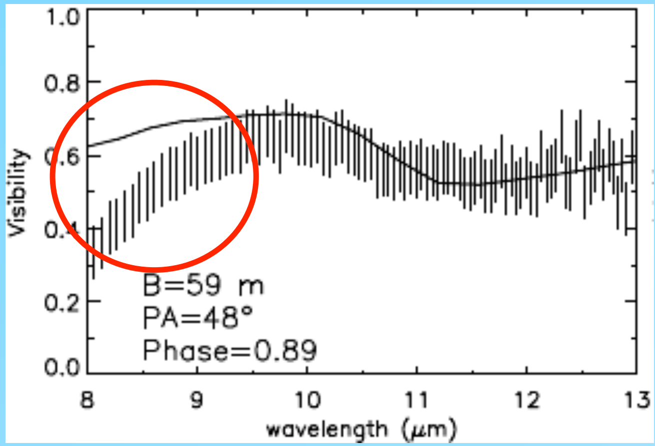


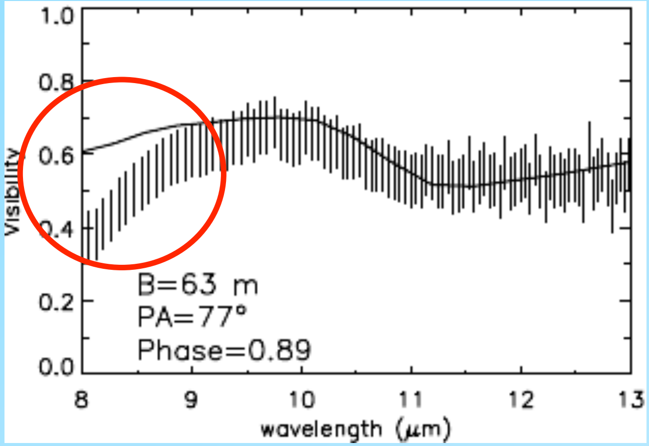
2 possible sources of disagreement:

- **The geometry of the object**: potential deviations from the spherical symmetry at certain position angles

- **The variability of the object**: the object is subsequently more or less extended from phase-to-phase

The molecular layer





The model is too optically thin in the 8.5 μm spectral band

The regions probed at the Sp.Freq. = 60 meter baseline / 8.5 μm are located between the photosphere and the dust shell inner radius.

Increase the optical thickness by adding an extended C_2H_2+HCN molecular layer located in this region and re-emitting in that spectral range: ***MOLsphere***

The *MOLsphere* is a non-consistent *ad hoc* model !

Step 3: Dynamic modeling of R Scl

Choice of a specific model among the grid of dynamical models:

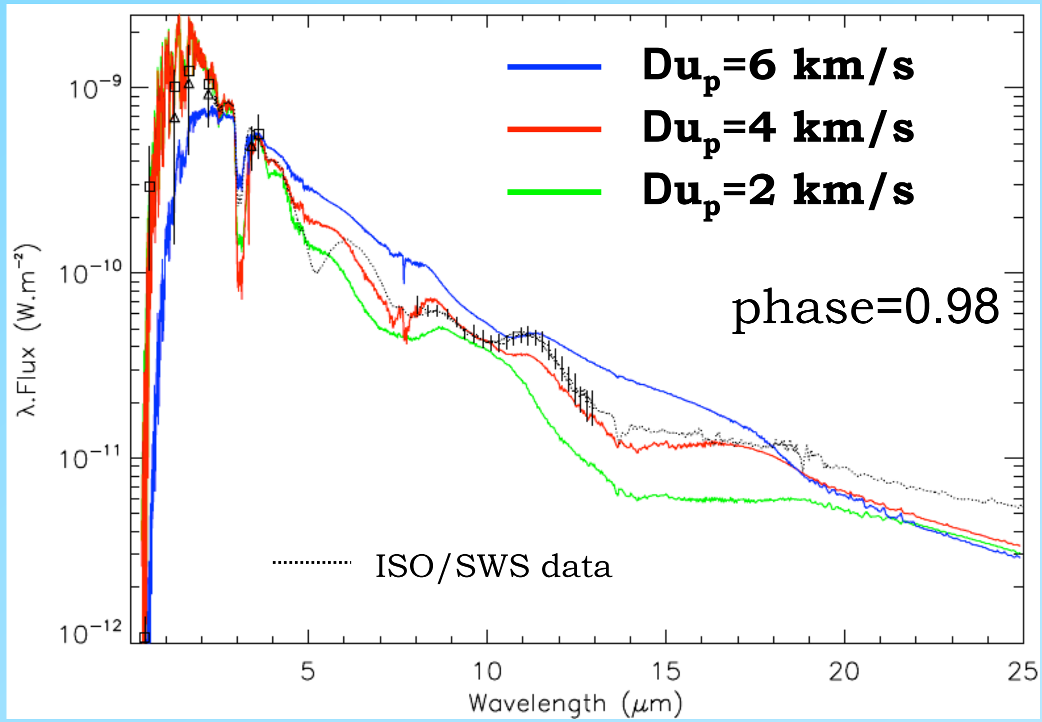
	T_{eff} (K)	C/O	L ($L_{\odot}$)	M ($M_{\odot}$)	Z ($Z_{\odot}$)	x (km/s)
hydrodynamic	**2800**	**1.35**	**7080**	**1**	**1**	**2.5**
hydrostatic	**2700**	**1.40**	**7000**	**1**	**1**	**2.5**

2 other free parameters are required:

- $\mathbf{P_{mod}}$: the pulsation period of the piston
  390 days, the closest to the pulsation period of R Scl (374 days)

- $\mathbf{Du_p}$: the amplitude of the piston velocity
  a range of [**2-6 km/s**] has been tested

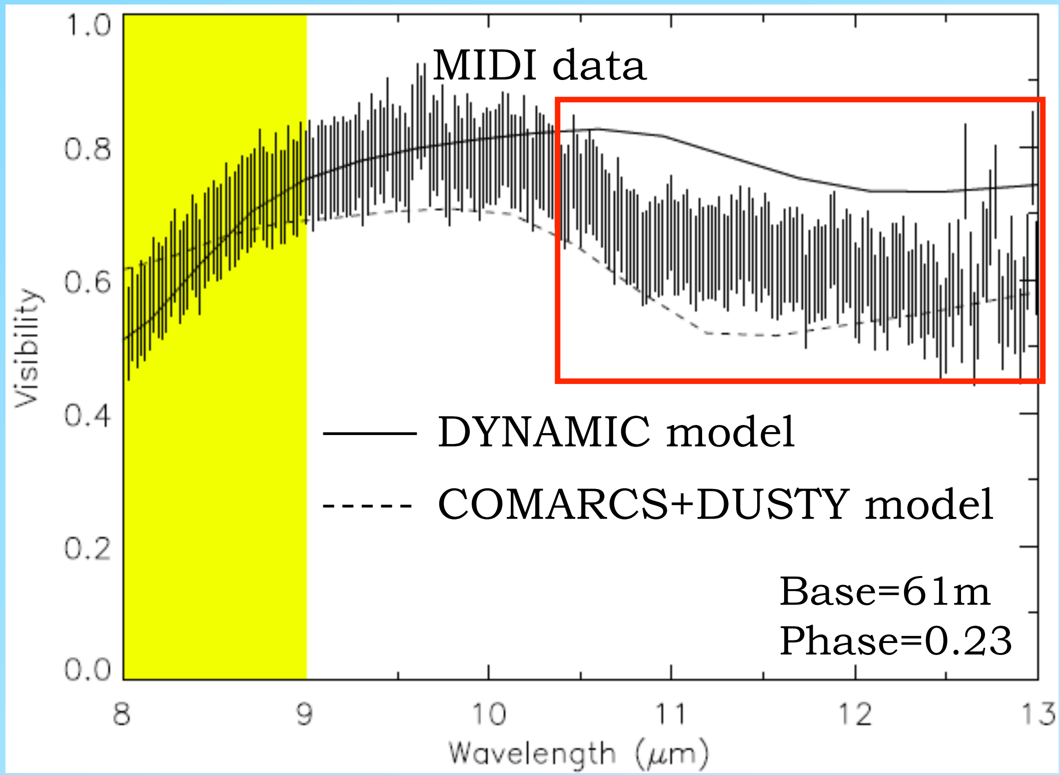
Amplitude of the piston velocity



- **Du_p>4 km/s:** filling up of the whole molecular features at wavelengths longwards of 3.5 μm (mass-loss > 10^{-6} $M_{\odot}$/yr)
- **Du_p<4 km/s:** dust-free pulsating atmosphere without any wind (no mass-loss) nor dust formation.

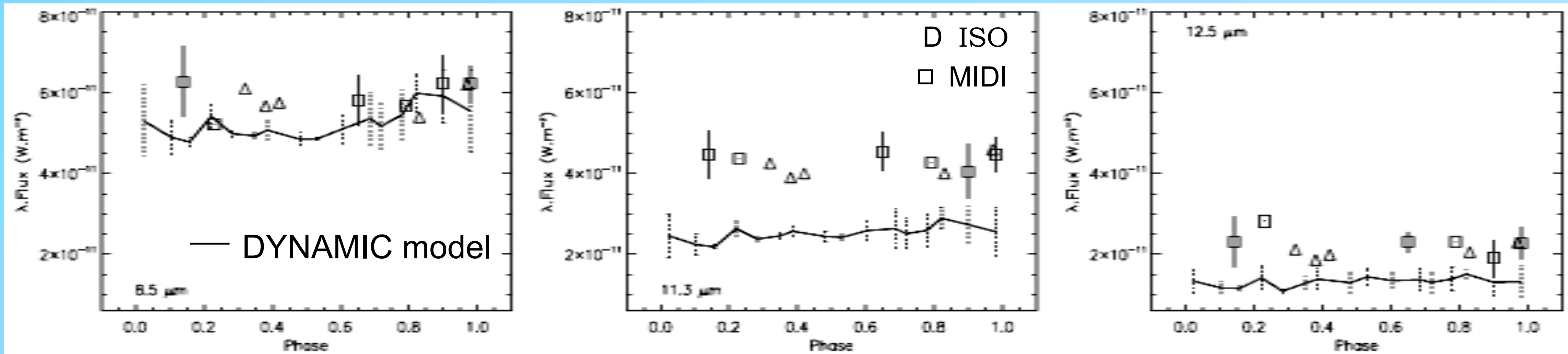
Du_p=4 km/s gives the best match of the overall spectrum

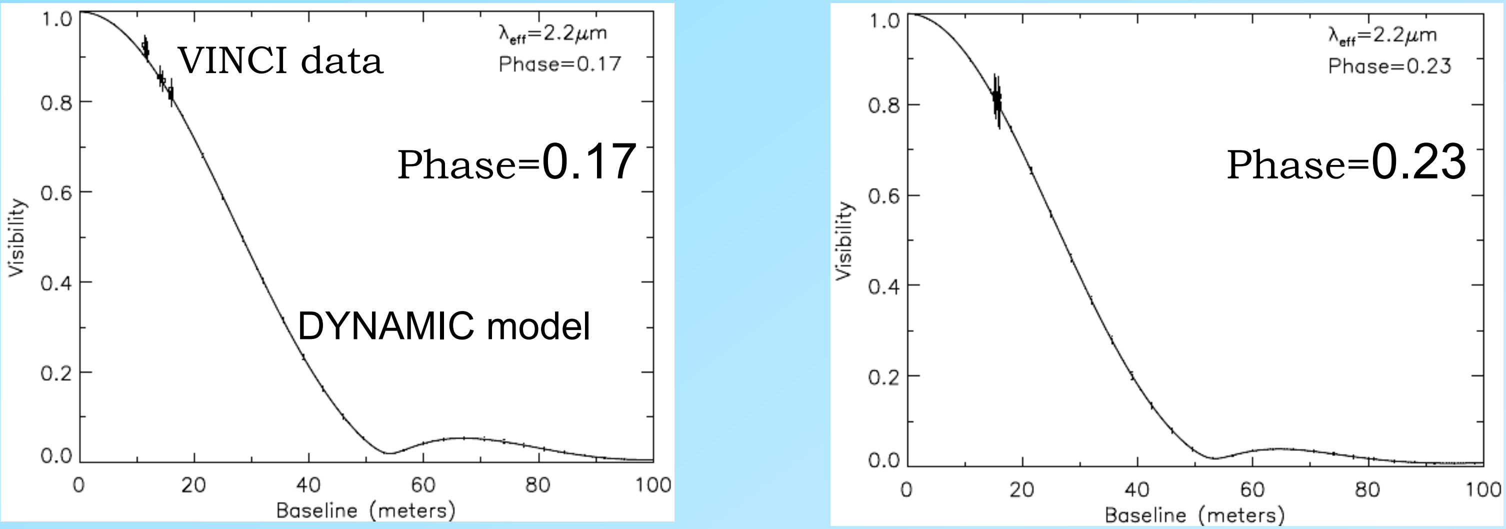
Self consistent formation of extended molecular structures

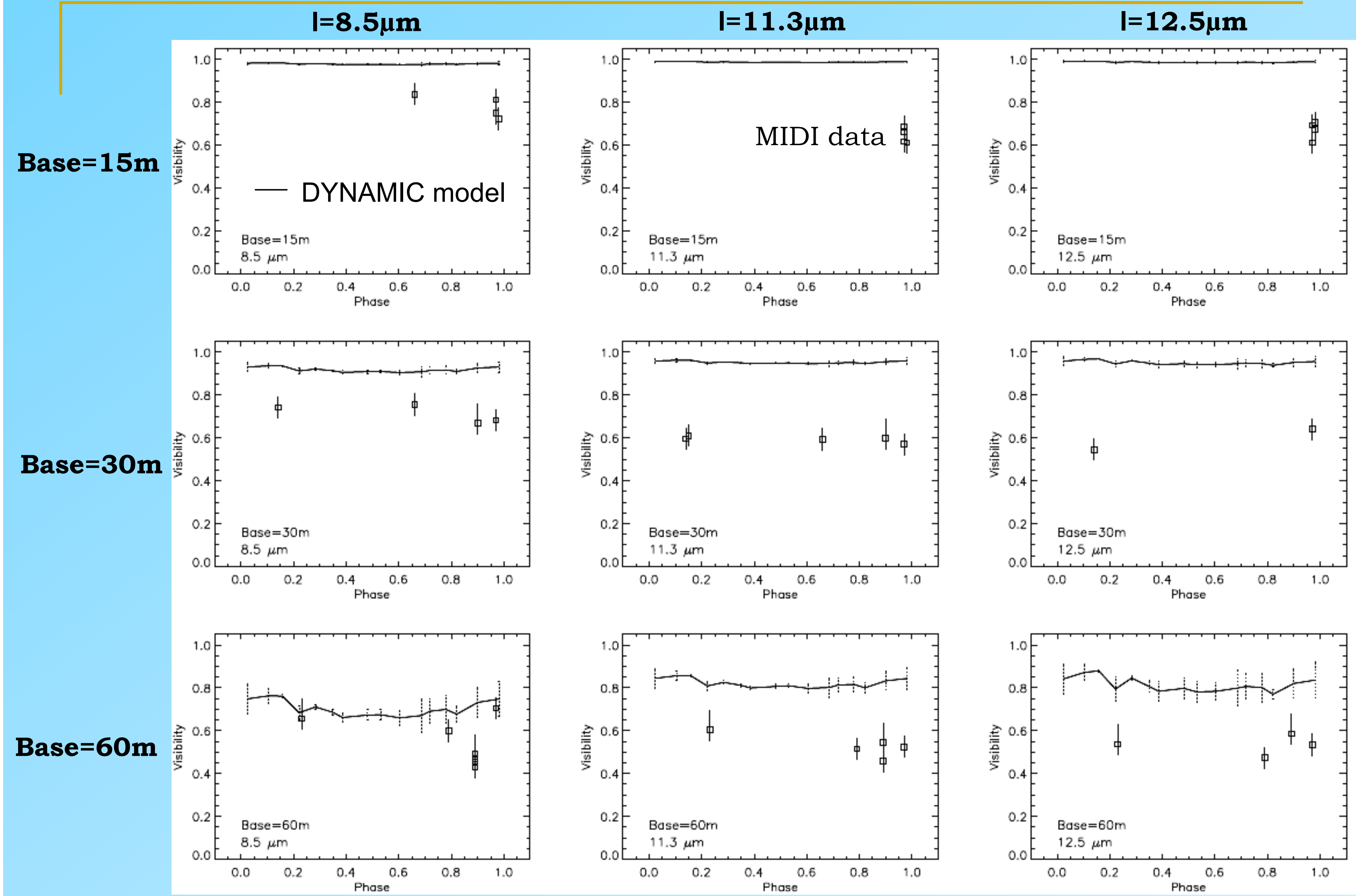


Extended molecular structures of C_2H_2 and **HCN** are predicted in a self-consistent way by the dynamic model whereas the COMARCS+DUSTY model failed to roproduce the slope in the 8-9 μm region

Comparison of the dynamic modeling results to the time dependent Spectro Interferometric data






l=8.5µm
l=11.3µm
l=12.5µm
Base=15m
Base=30m
Base=60m
DYNAMIC model
MIDI data
Visibility
Phase
Base=15m
8.5 µm
Base=15m
11.3 µm
Base=15m
12.5 µm
Base=30m
8.5 µm
Base=30m
11.3 µm
Base=30m
12.5 µm
Base=60m
8.5 µm
Base=60m
11.3 µm
Base=60m
12.5 µm

Disagreement between the DYNAMIC model and the observations

1. The inaccurate estimation of the parameter values of the hydrostatic initial structure.
2. The differences between the parameter values deduced from the hydrostatic COMARCS modeling and the parameter values of the hydrostatic initial structure of the hydrodynamic model.
3. The inclusion of SiC (not included in the dynamic computations) in the a posteriori radiative transfer calculation.
4. The approximation of the stellar pulsation with the sinusoidal piston.
5. The sparse sampling of the transition region from windless models to models with considerable outflows in certain critical stellar parameters.
6. The approximation of a complete momentum and position coupling of gas and dust in the dynamic computations.
7. The approximation of the small-particle limit (or Rayleigh limit) in the determination of the dust grain opacity in the dynamic computations.

Conclusions and perspectives

We present the first interpretation of combined photometric, spectrometric and interferometric measurements of a carbon-rich star based on state-of-the-art self-consistent dynamic atmospheric models.
(Sacuto, Aringer, Hron, Nowotny, Paladini, Verhoelst, Höfner, A&A acc.)

Extended molecular structures of C_2H_2 and HCN are predicted in a self-consistent way.

Rather good agreement is found with the overall distribution of the spectro-photometric data from 0.4 to 25 μm.

VINCI visibilities are well reproduced for the two post-maximum brightness phases meaning that the dynamic model structure is suitable in the near-infrared spectral band.

In the mid-infrared, the dynamic model structure is not able to reproduce the more extended and dense dusty environment.

Due to the strong non-equilibrium process of dust formation, the transition from models without wind to models with considerable mass-loss rates occurs in a very narrow parameters (**Du_p** , T_{eff} , C/O) range.

It seems necessary to improve the sampling of critical regions in parameter space in the grid of hydrodynamic models for further investigations of the extended structures of low mass-loss carbon stars.

The complete dynamic coupling of gas and dust, and the approximation of grain opacities with the small-particle limit unsuitable for low mass-loss rate object, could also contribute to the disagreement.

First tests with C-star models based on opacities that take grain size into consideration (Mattsson & Höfner, in prep.) show that wind characteristics may be affected considerably in models close to a mass-loss threshold (Mattsson et al., 2009), in resemblance to recent wind models for M-type AGB stars (Höfner, 2008).

THANK YOU