Wind formation and mass-loss on the AGB

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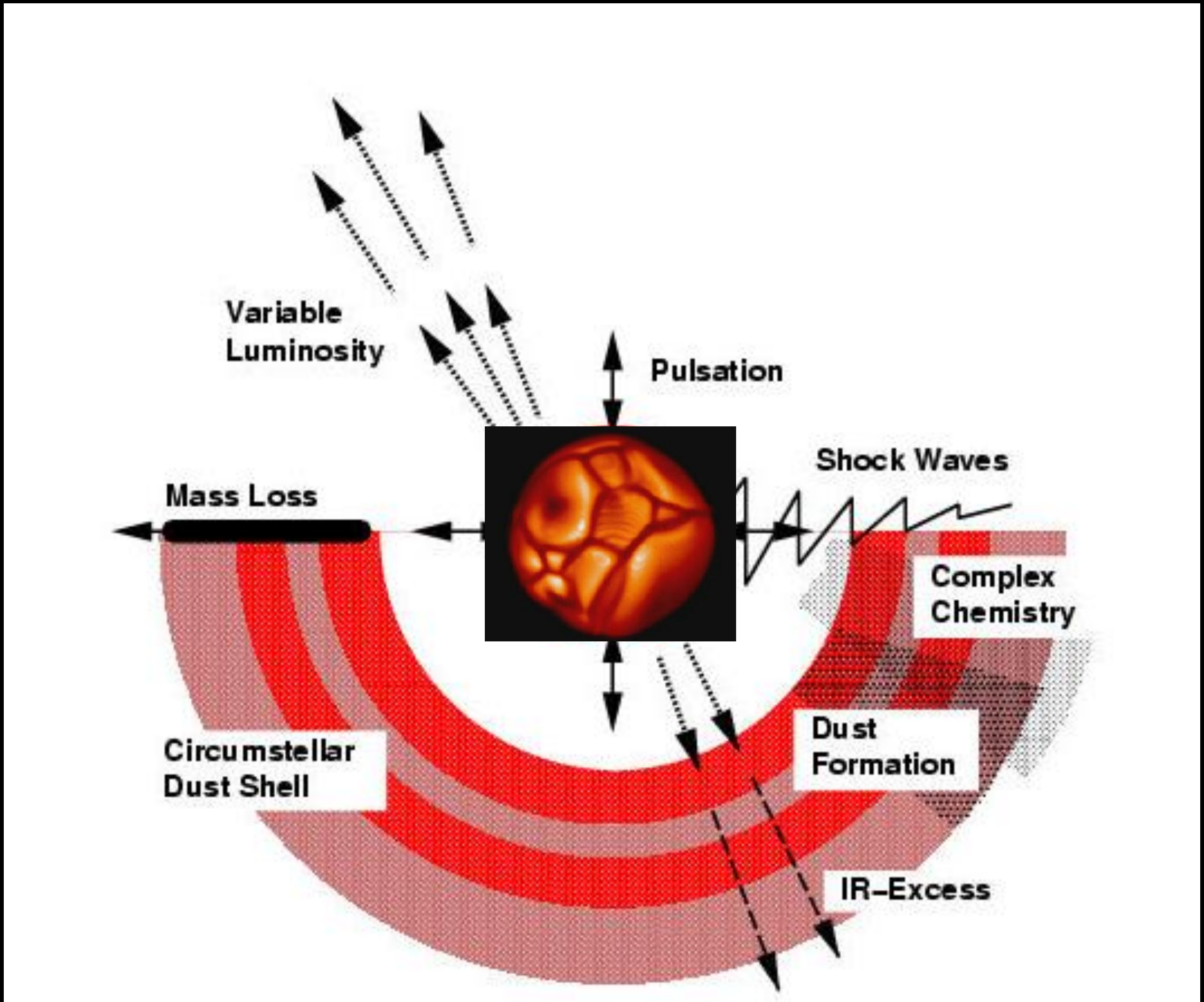
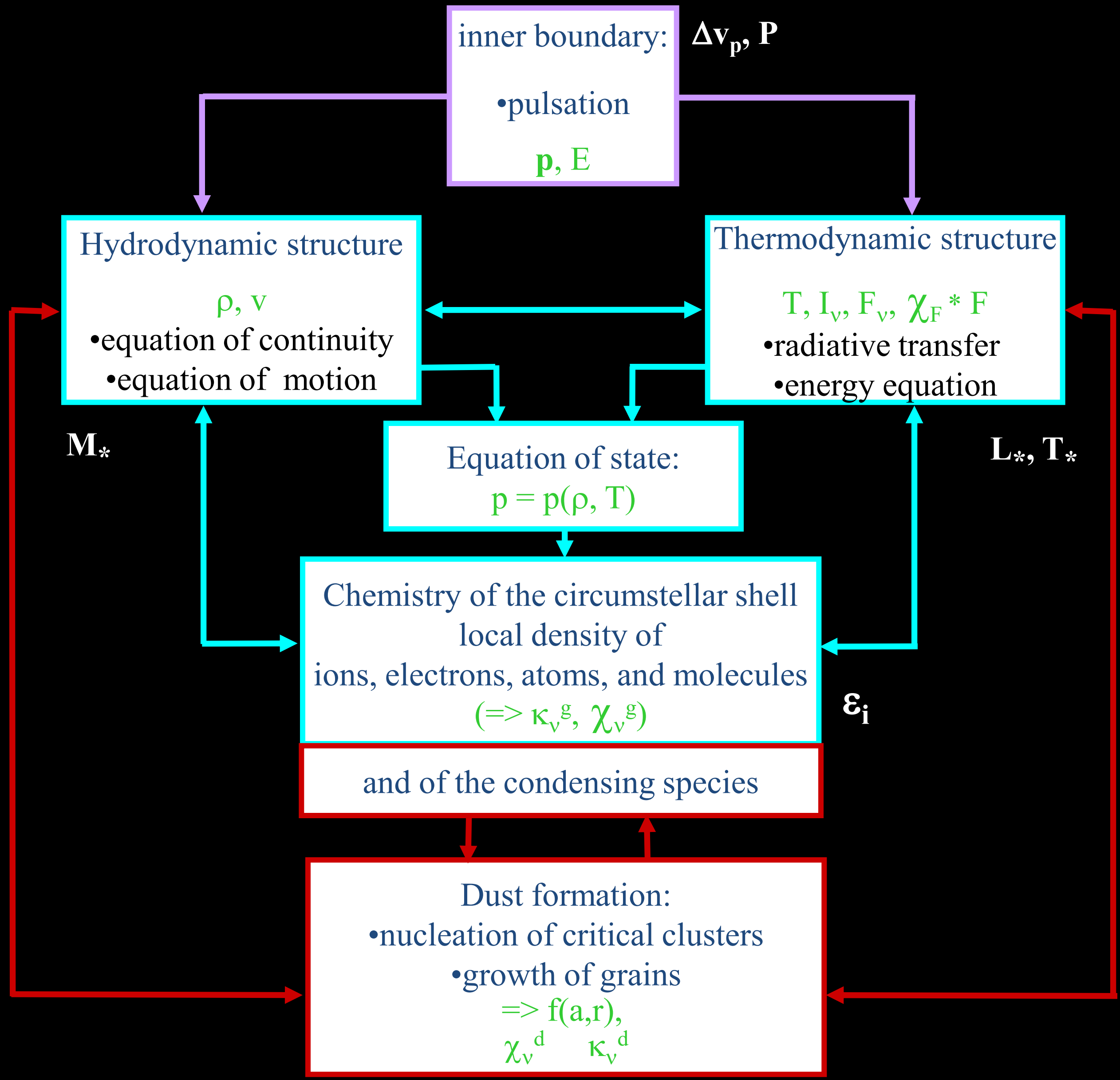
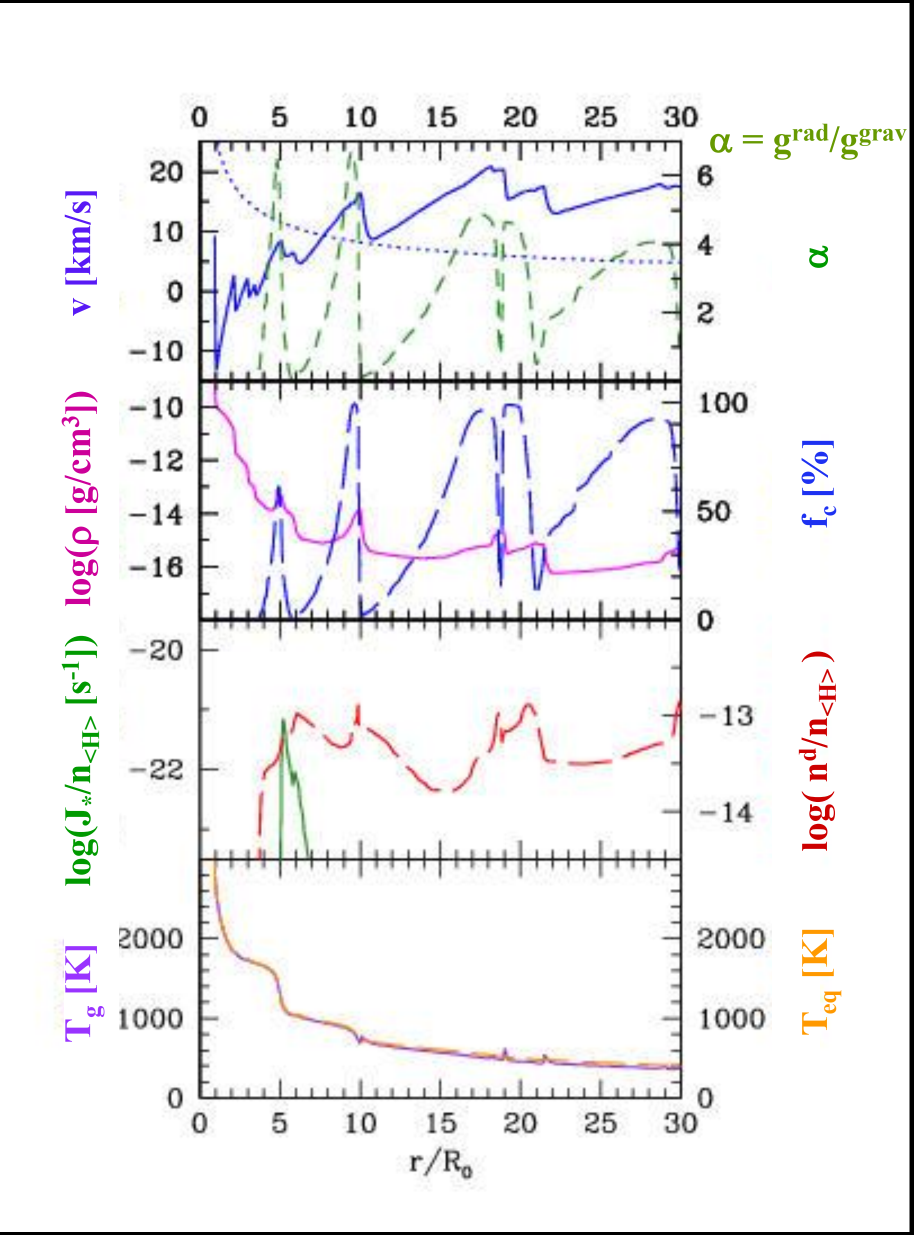
Scenario of a dust forming circumstellar shell



Consistent Model



Radial structure of a high mass-loss rate model



M_* = 0.8 M_o

L_* = 1.5 10^4 L_o

T_* = 3000 K

$\varepsilon_C/\varepsilon_O$ = 1.30

P = 650 d

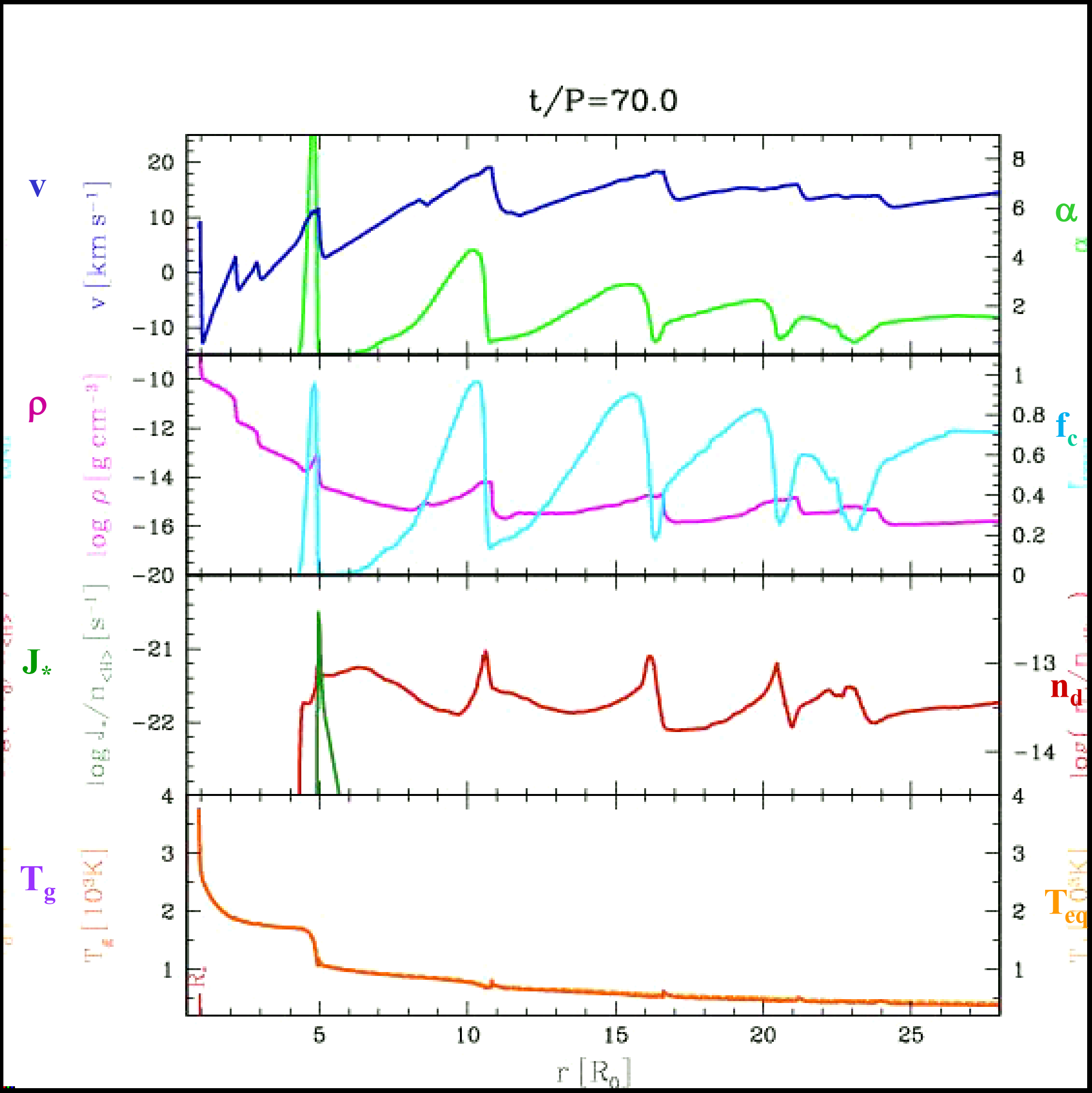
Δv_p = 8 km/s

$\dot{M}$ = 4.5 10^{-5} M_o/yr

v_{exp} = 17.3 km/s

ρ^d/ρ^g = 1.1 10^{-3}

Temporal evolution of a high mass-loss rate model



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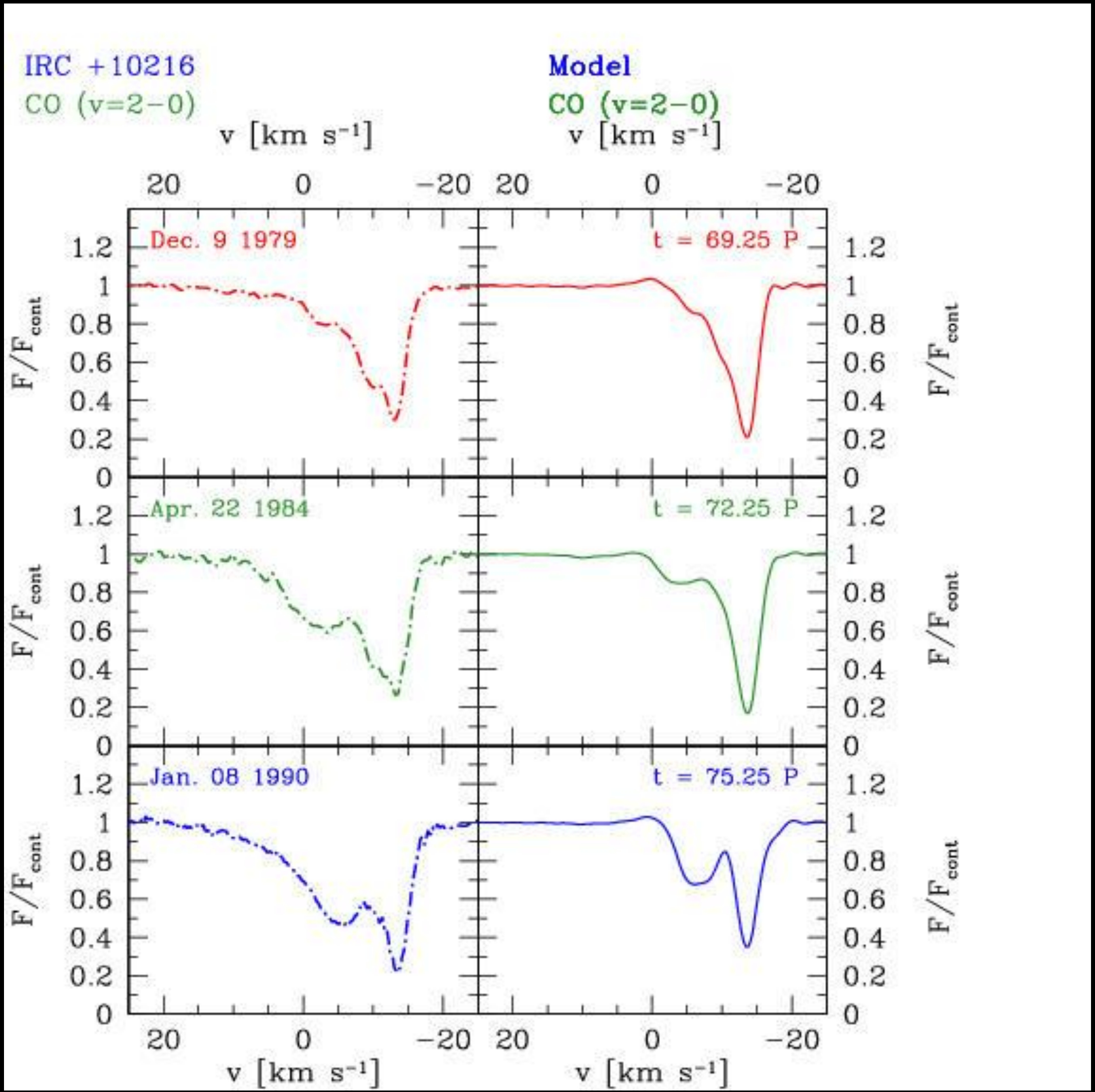
$v_{exp} = 17.3$ km/s

$\rho^d/\rho^g = 1.1\ 10^{-3}$

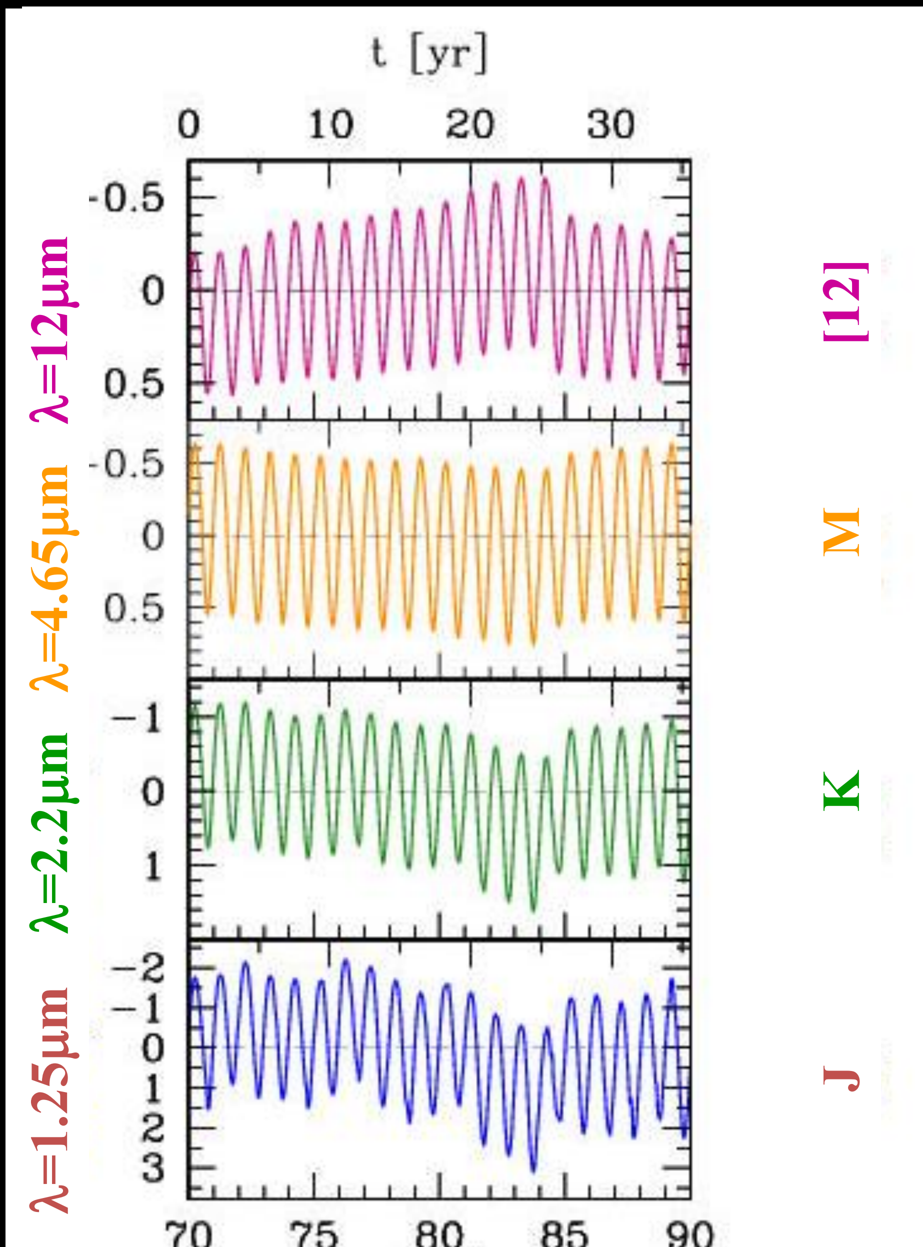
IRC +10216: CO infrared lines

Observation - Calculation



Winters et al. 2000, A&A 359, 651

Light curves of a high mass-loss rate model



$M_* = 0.8\ M_o$

$L_* = 1.5\ 10^4\ L_o$

$T_* = 3000$ K

$\varepsilon_C/\varepsilon_O = 1.30$

$P = 650$ d

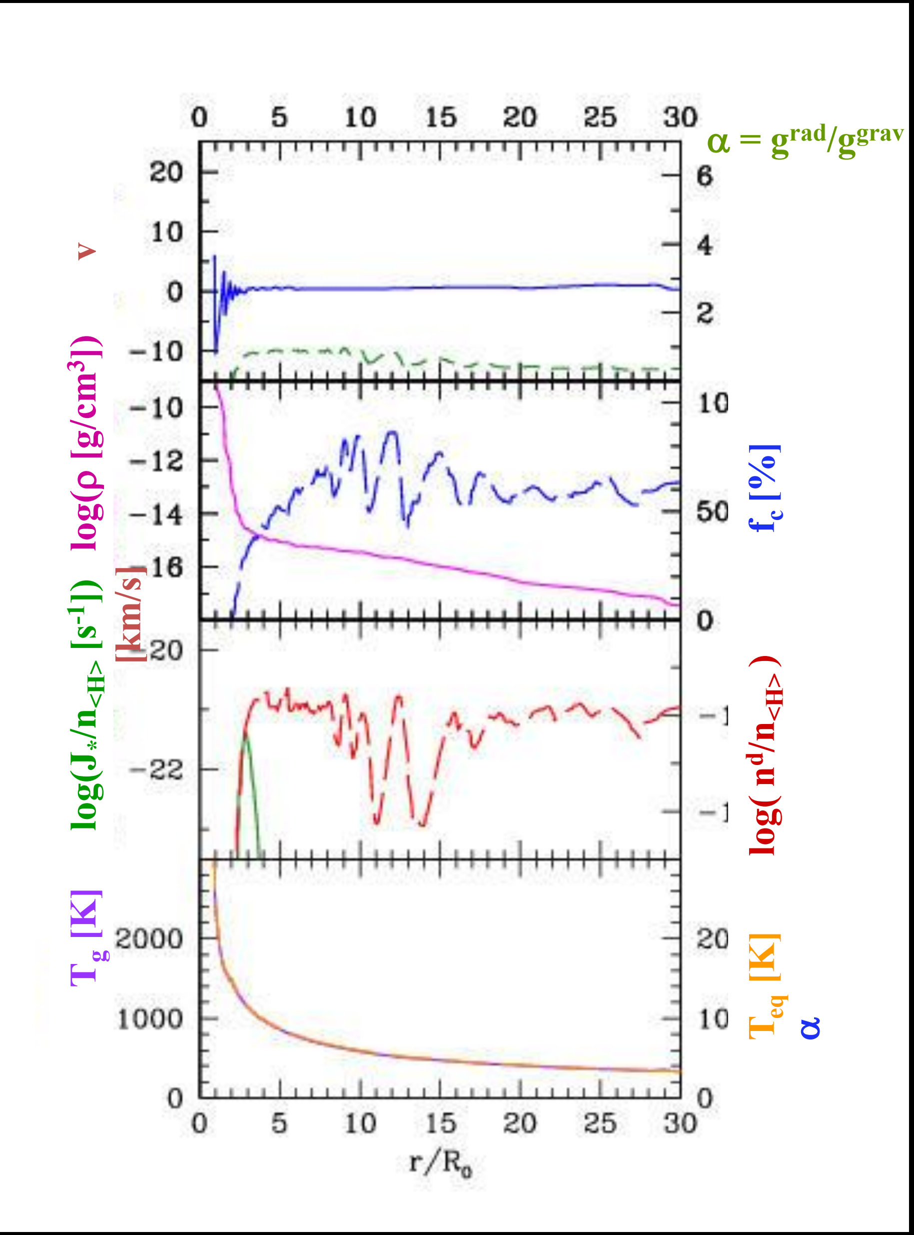
$\Delta v_p = 5$ km/s

$\dot{M} = 4.5\ 10^{-5}\ M_o/yr$

$v_{exp} = 17.3$ km/s

$\rho^d/\rho^g = 1.1\ 10^{-3}$

Radial structure of a low mass-loss rate model



$M_* = 0.8\ M_o$

$L_* = 0.5\ 10^4\ L_o$

$T_* = 2600$ K

$\varepsilon_C/\varepsilon_O = 1.30$

$P = 250$ d

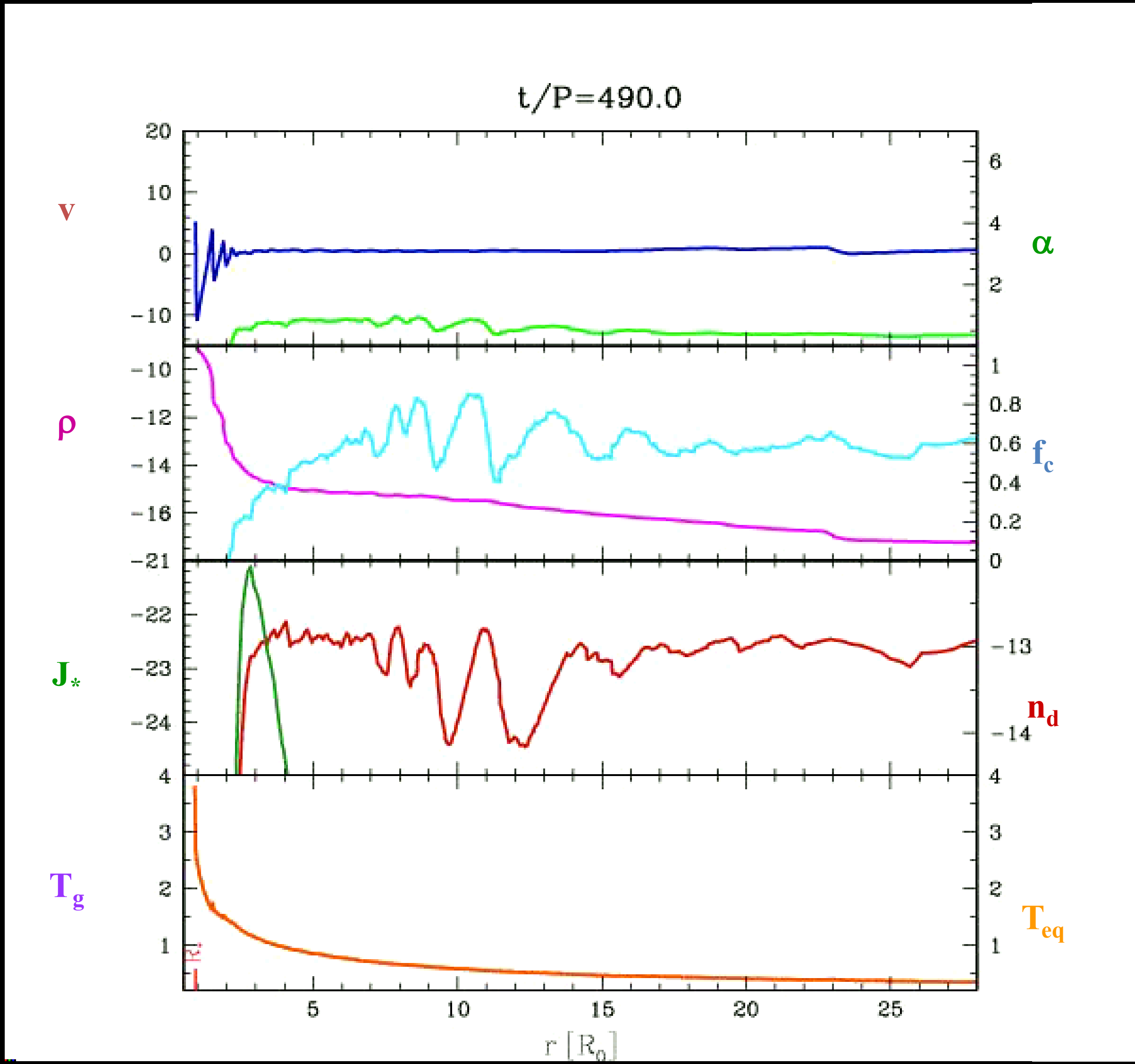
$\Delta v_p = 5$ km/s

$\dot{M} = 1.2\ 10^{-7}\ M_o/yr$

$v_{exp} = 2.4$ km/s

$\rho^d/\rho^g = 0.8\ 10^{-3}$

Temporal evolution of a low mass-loss rate model



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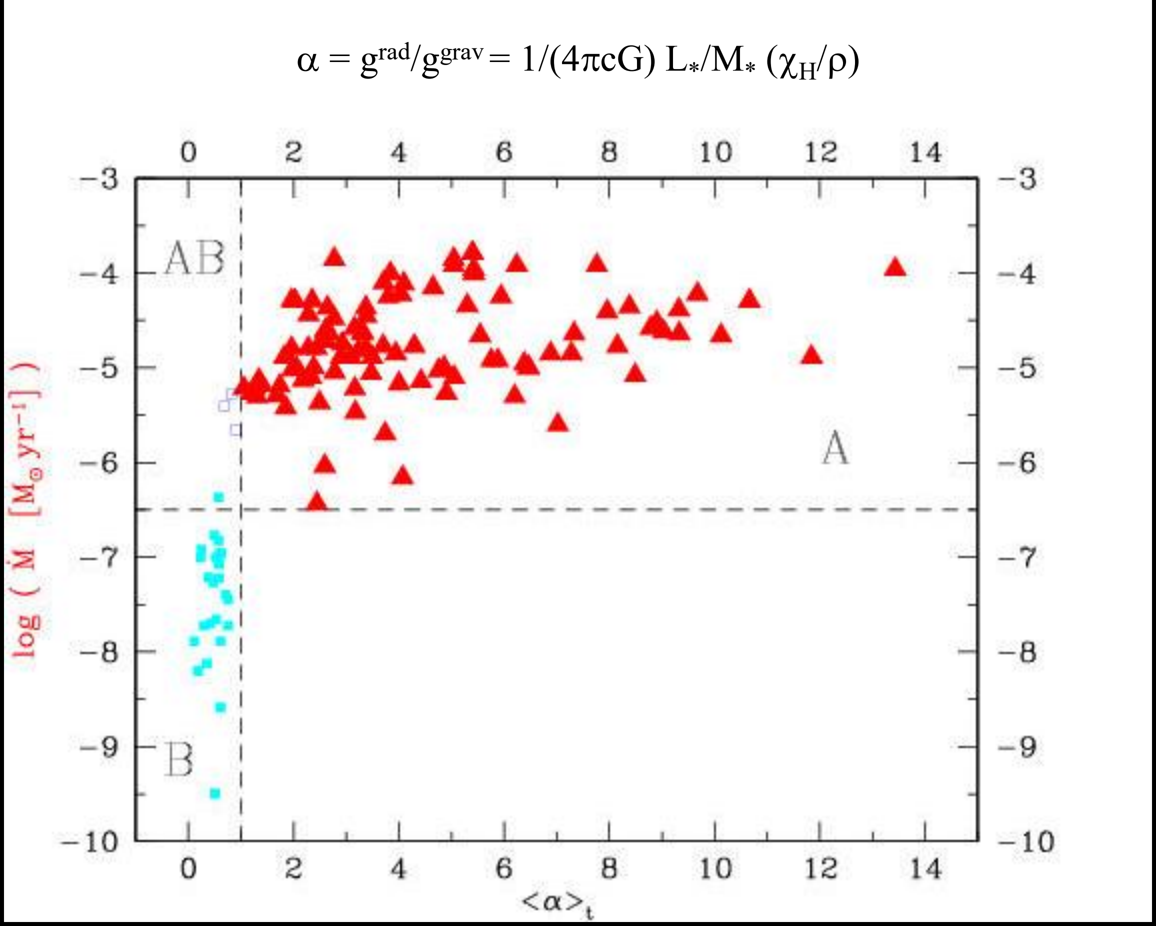
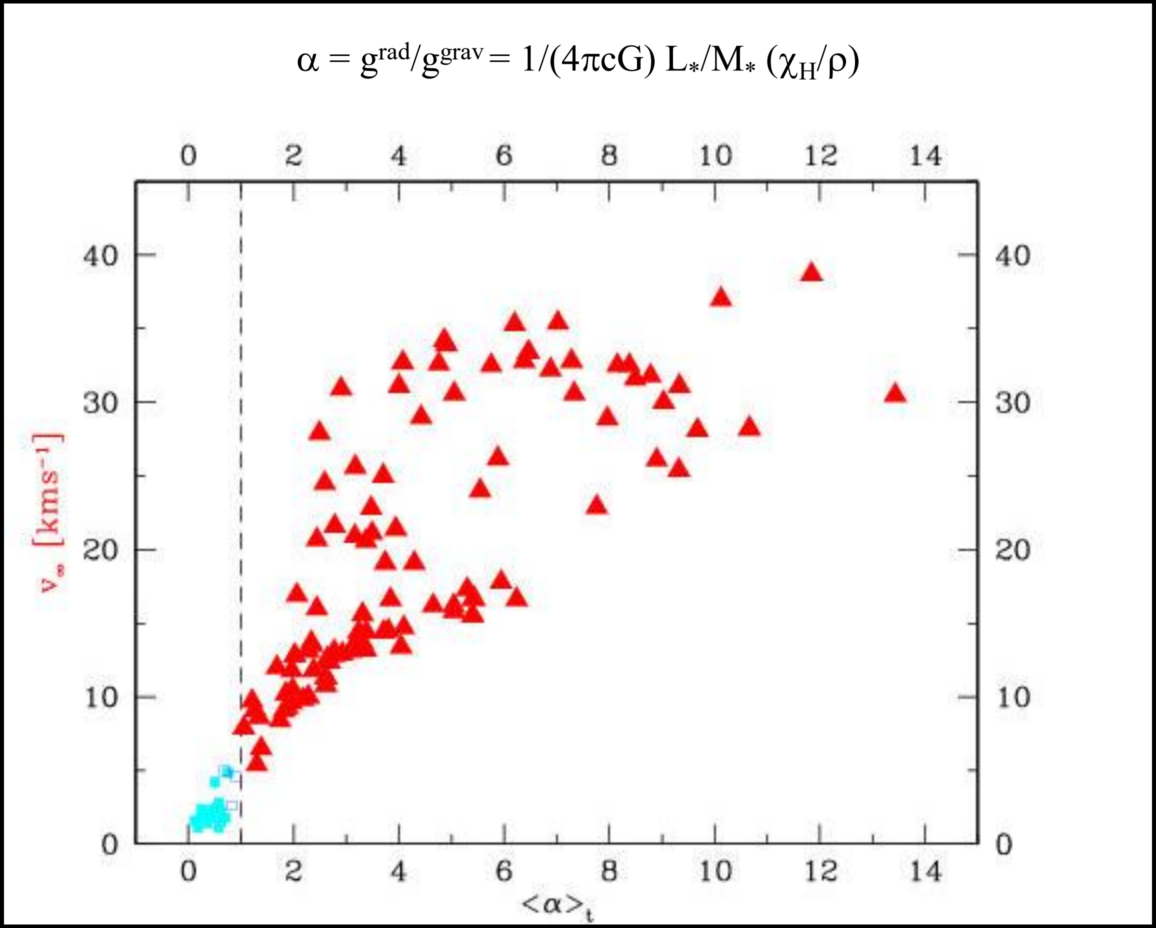
v_{exp} = 2.4 km/s
$\rho^d/\rho^g = 0.8\ 10^{-3}$

Topology of solution space



Winters et al. 2000, A&A 361, 641

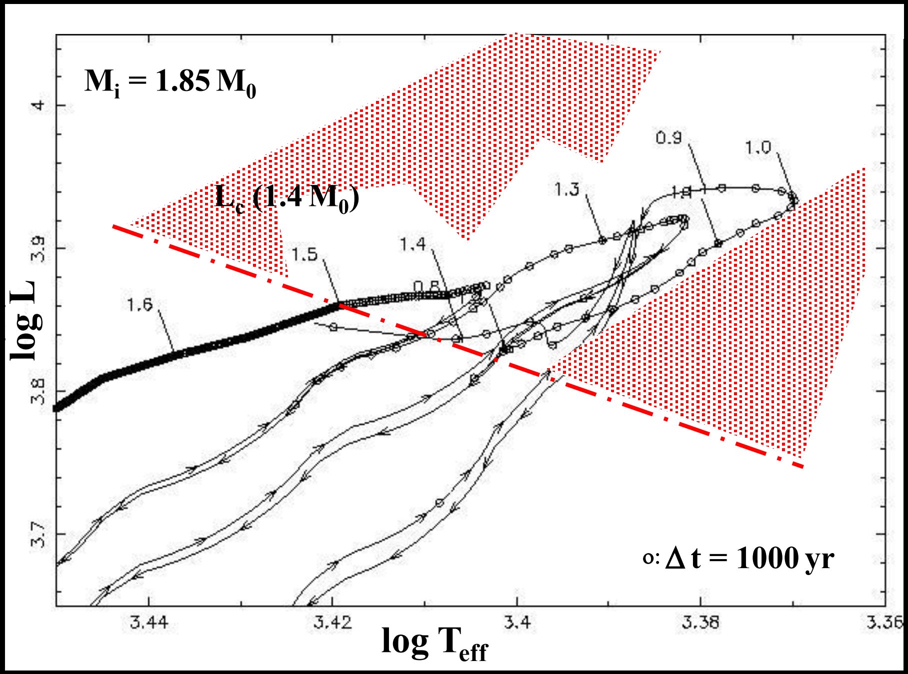
Low mass-loss rate => low velocity

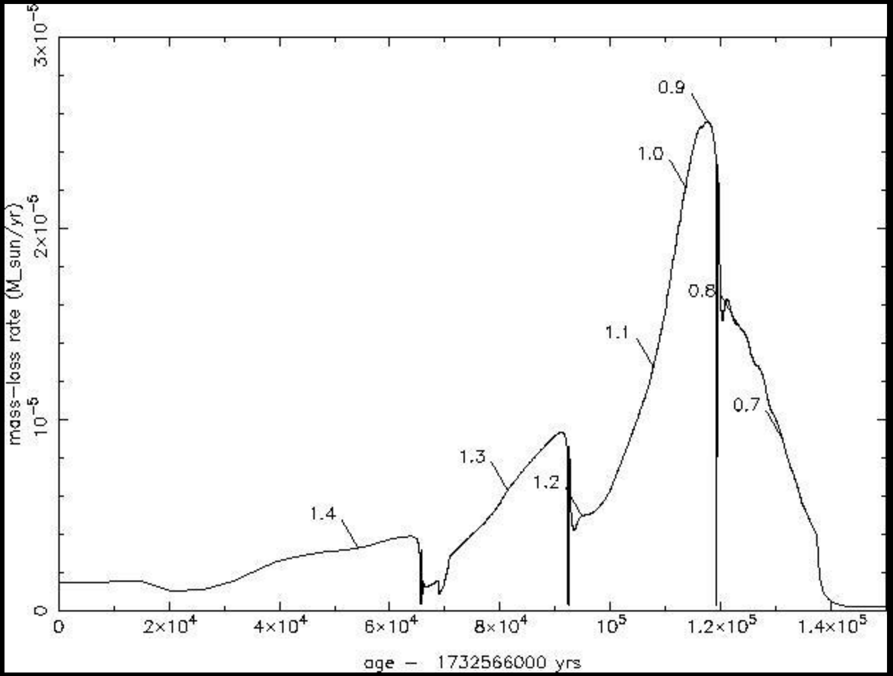


Winters et al. 2000, A&A 361, 641

Continuous mass-loss: short interruptions

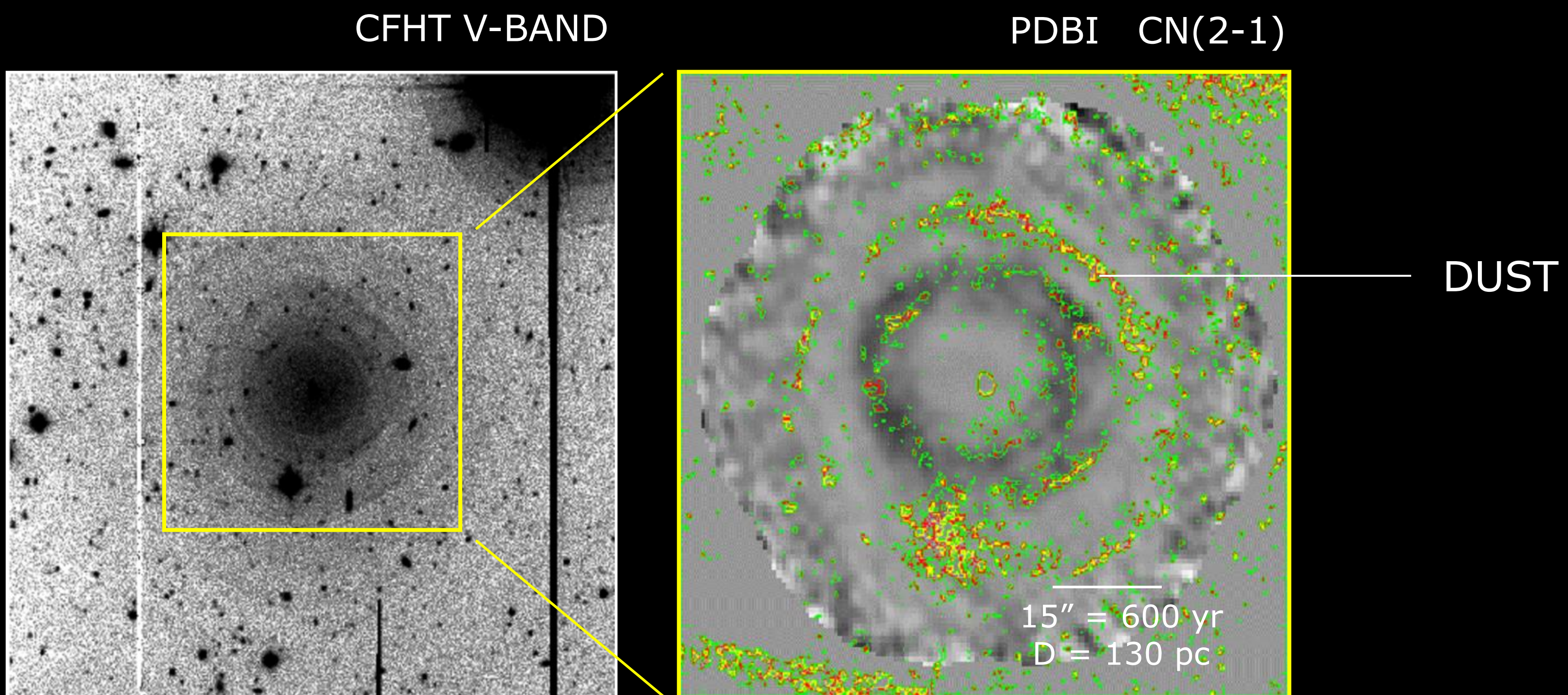
for $M_i > 1.3\ M_o$ => „superwind“





Schröder, Winters, & Sedlmayr 1999, A&A 349, 898

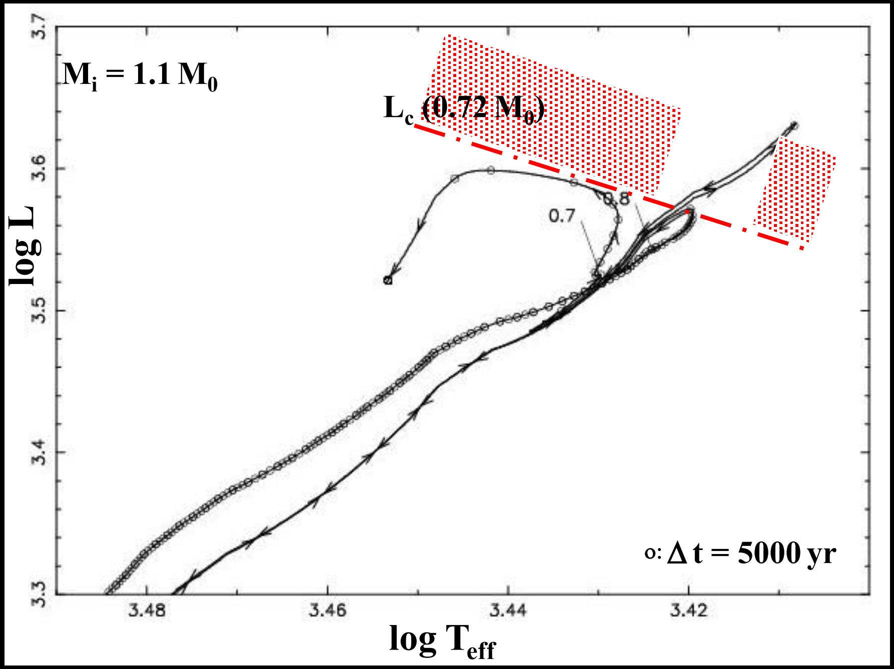
Carbon star IRC+10216

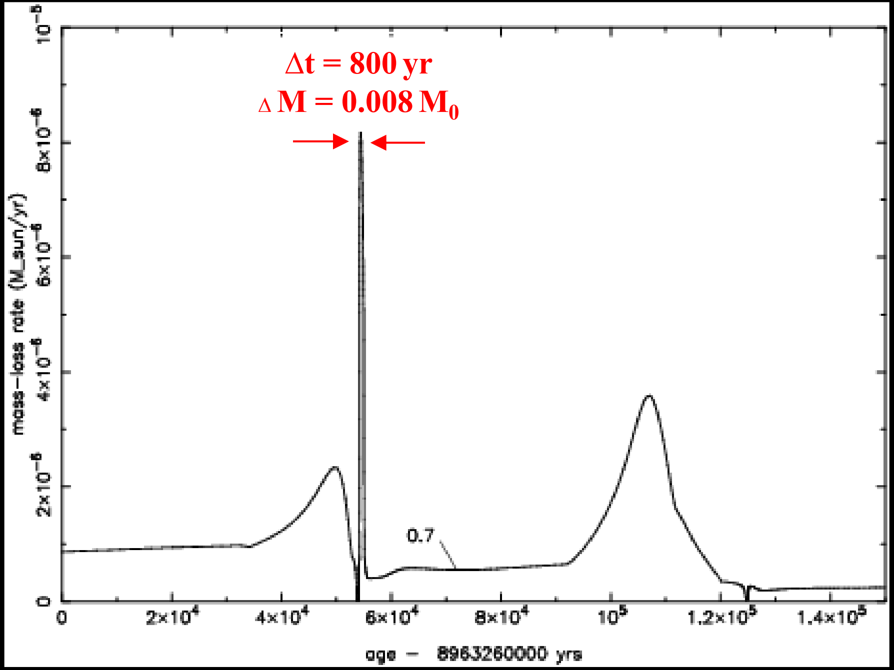


Mauron & Huggins (1999) A&A, 315, 284 *Guélin et al. (2000) IAU Symp 197, 365*

Transition B - A - B: e.g., thermal pulse

for $M_i < 1.3\ M_o$ => detached shell





Schröder, Winters, & Sedlmayr 1999, A&A 349, 898

Olofsson et al. 2000:

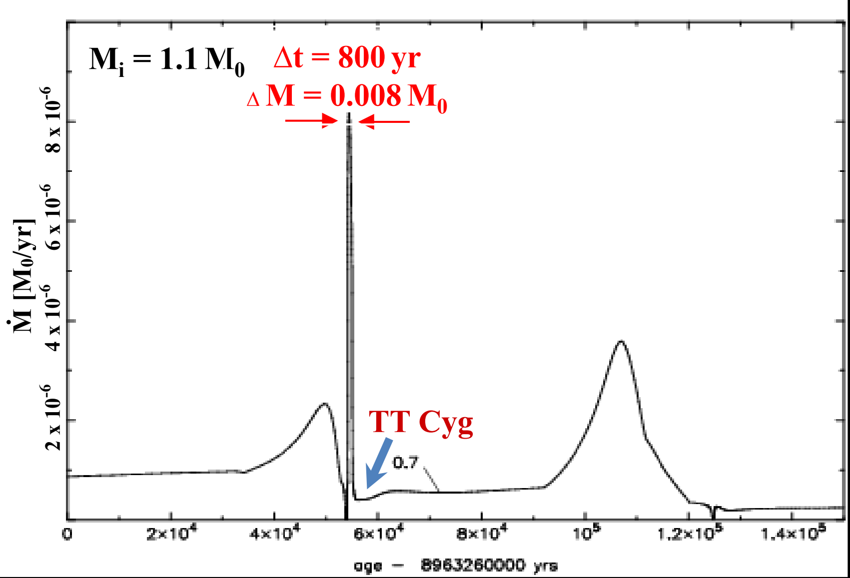
Carbon star TT Cyg

detached shell:

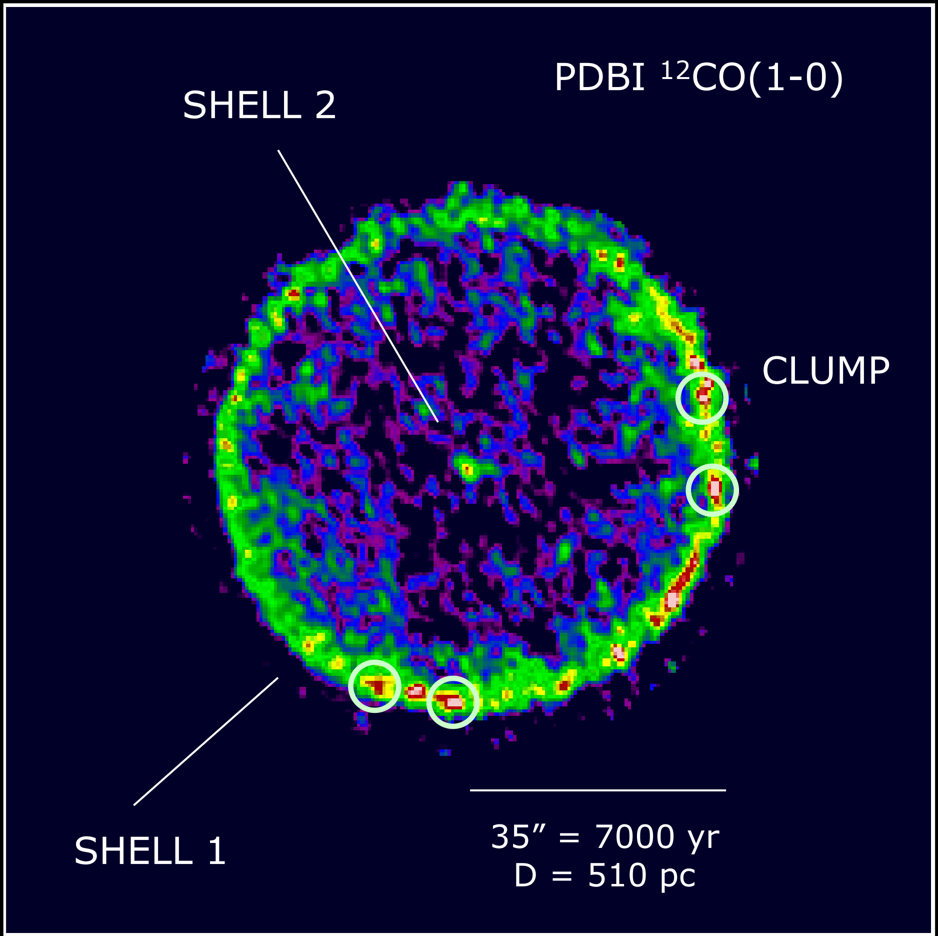
$\dot{M} \approx 10^{-5}\ M_0/yr$
$v_{exp} = 12.6$ km/s
$\Delta M = 0.007\ M_0$
$\Delta t = 500$ yr

present day:

$\dot{M} = 3\ 10^{-8}\ M_0/yr$
$v_{exp} = 3.8$ km/s



Schröder, Winters & Sedlmayr (1999)



Olofsson et al. (2000) A&A, 353, 383

The hydrodynamical structure of AY Vir

Observation:

CO (2-1): v_{exp} = 4.5 km/s

SiO (v=1,2-1): v_{phot} ~ ±11 km/s

derived $\dot{M}$ ~ 2 10^{-7} M_o/yr

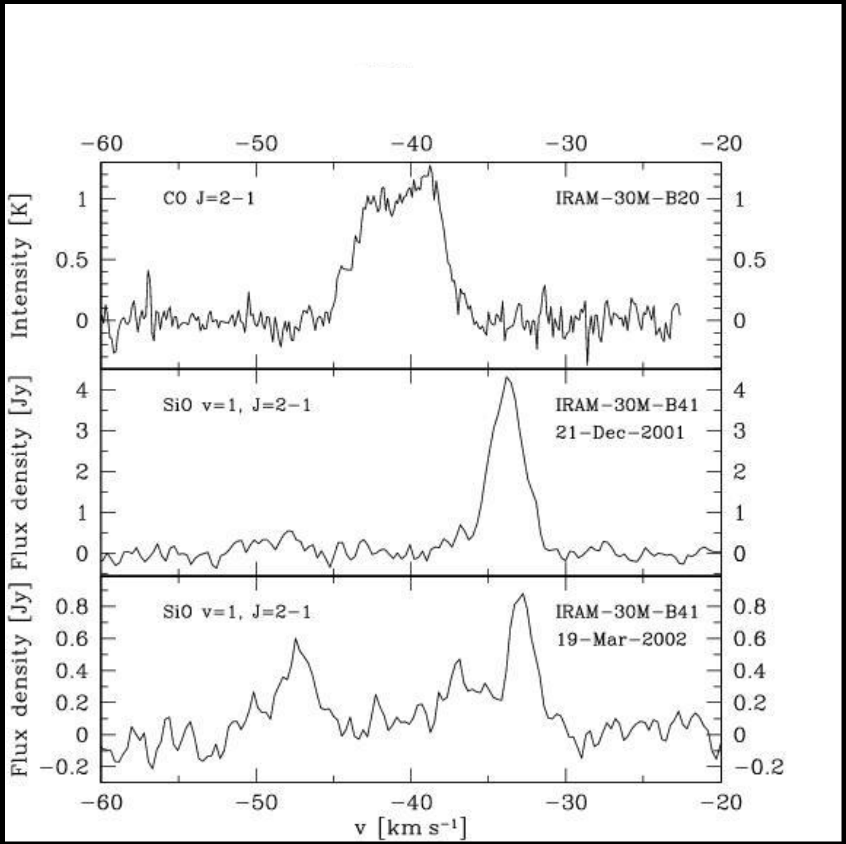
B-type model:

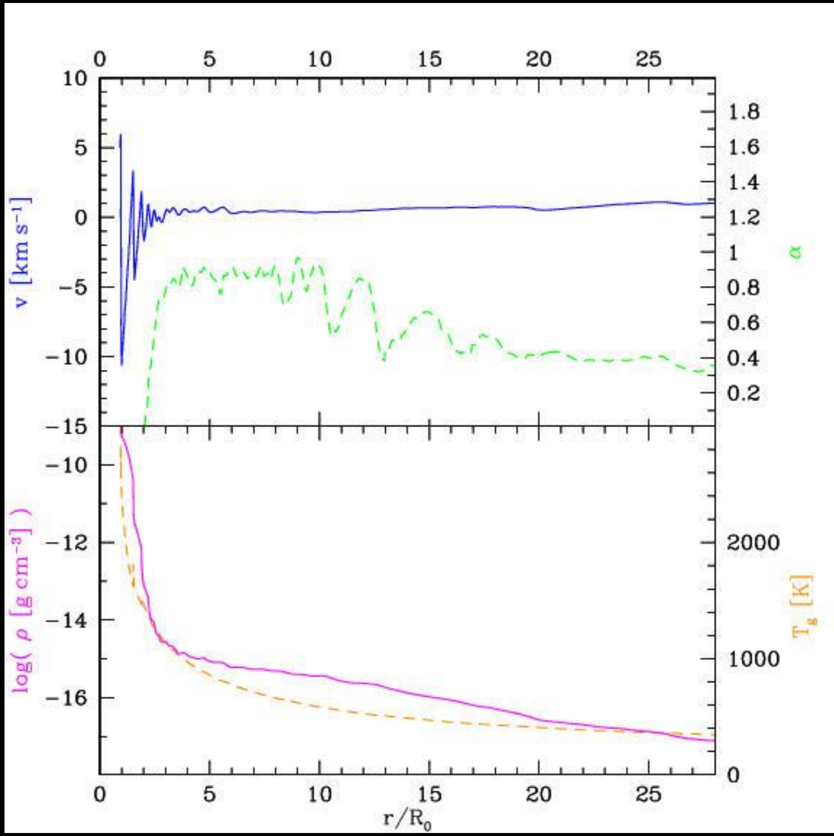
v_{exp} = 2.4 km/s

v_{phot} ~ ±10 km/s

$\dot{M}$ = 1.2 10^{-7} M_o/yr

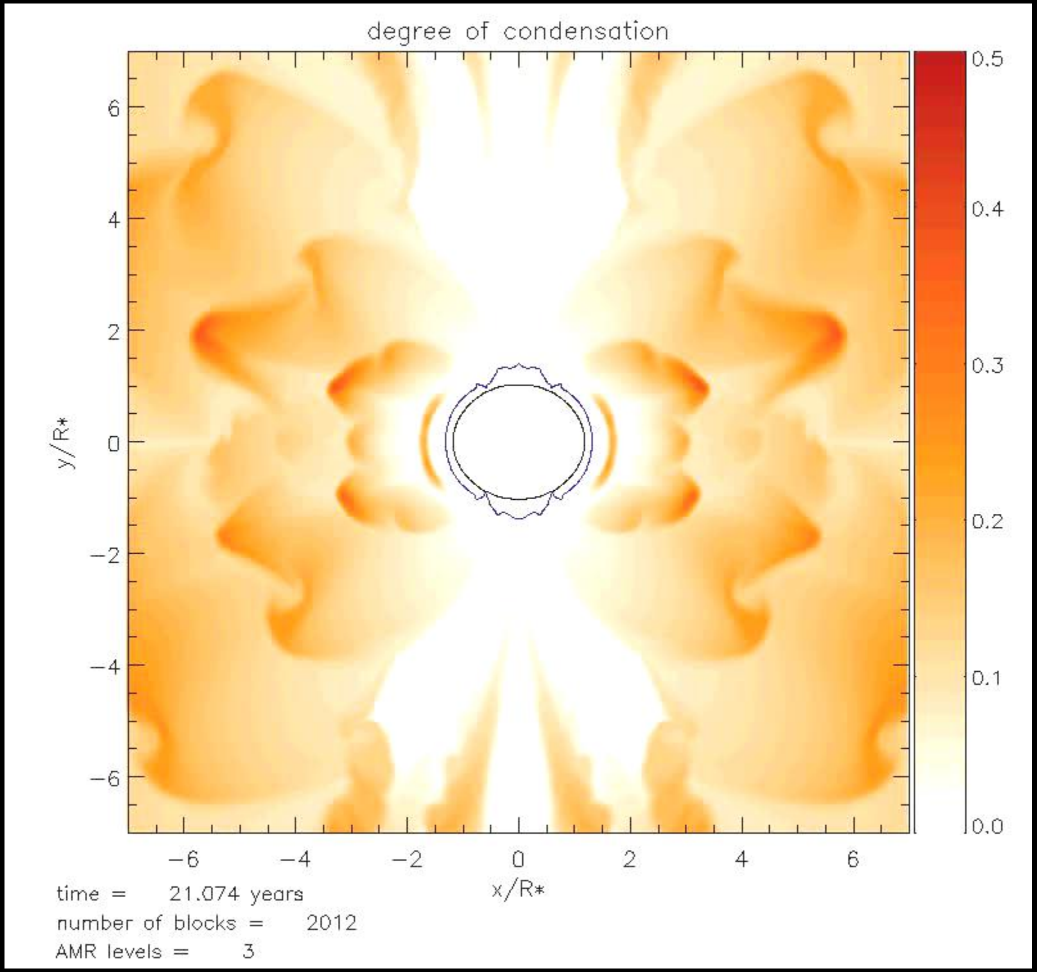
Winters et al. 2003, A&A 409, 715





Multi-D models (I)

2-D axisymmetric models of the circumstellar dust shell **(Woitke 2006, A&A 452, 537)**



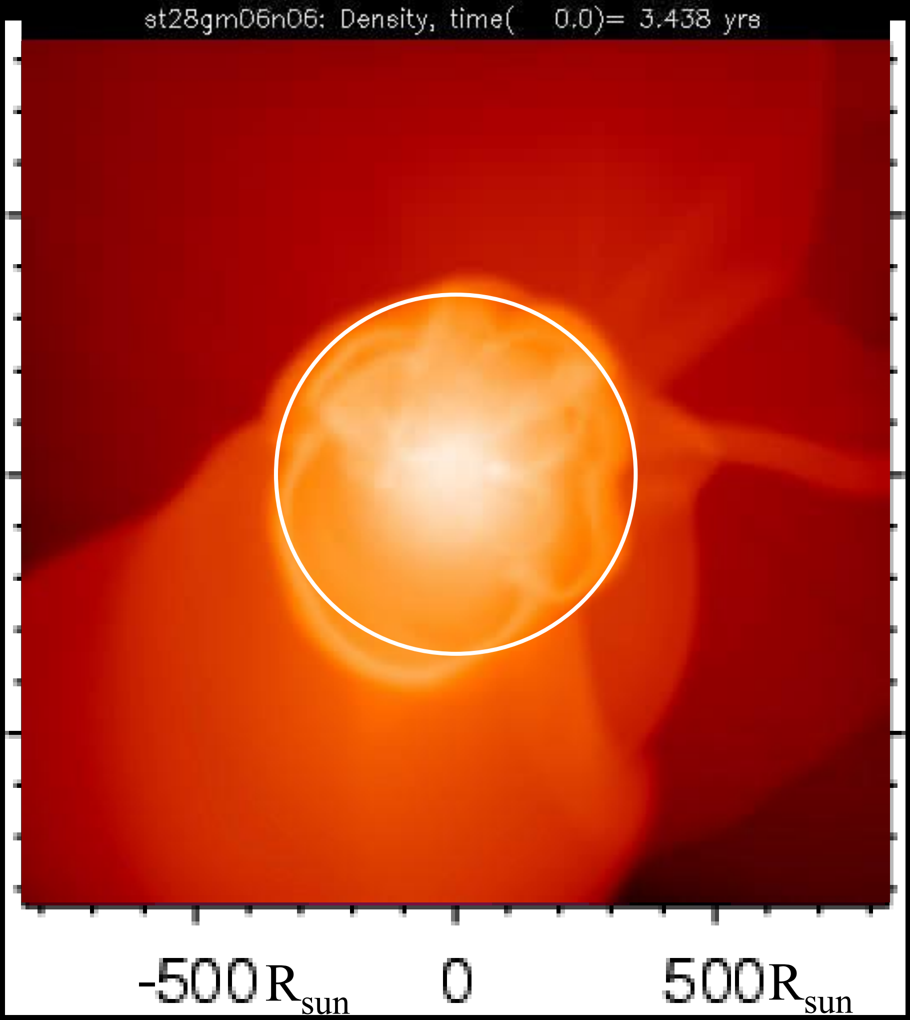
$M_* = 1.0\ M_o$
$L_* = 0.5\ 10^4\ L_o$
$T_* = 2500$ K

$\varepsilon_C/\varepsilon_O = 1.40$
$P = 365$ d
$\Delta v_p = 3$ km/s

$\dot{M} = 7.3\ 10^{-7}\ M_o$/yr
$v_{exp} = 18$ km/s
$\rho^d/\rho^g = 0.36\ 10^{-3}$

Multi-D models (II)

3-D models of convective envelope and inner atmosphere **(Freytag & Höfner 2008, A&A 483, 571)**



Conclusions

Dust formation has to be treated in a consistent way,
i.e. taking into account the coupling of the dust component to its surroundings

Time-dependent hydrodynamic models of pulsating, dust forming circumstellar shells reveal nonlinear phenomena induced by the self-regulating dust formation process

spatial structuring of the dust shell
dust induced shocks
back-warming
temporal structuring of the shell, eigen-timescale

Multi-dimensional models are becoming available:

$\Rightarrow$ **2-D axisymmetric, time dependent dust-driven wind models**

$\Rightarrow$ **3-D models of convective envelope and inner atmosphere**

Open questions

Oxygen-rich nucleation seeds

TiO_2? => Jeong et al. 2000,2003, Lee et al. 2015
SiO? => Gail et al. 2013
Al_2O_3? => Gobrecht et al. 2016

No consistent wind model for Supergiants

Convection?

No complete model yet

Stellar interior-atmosphere-circumstellar envelope