Dust formation around old stars and its feedback on the dust forming system

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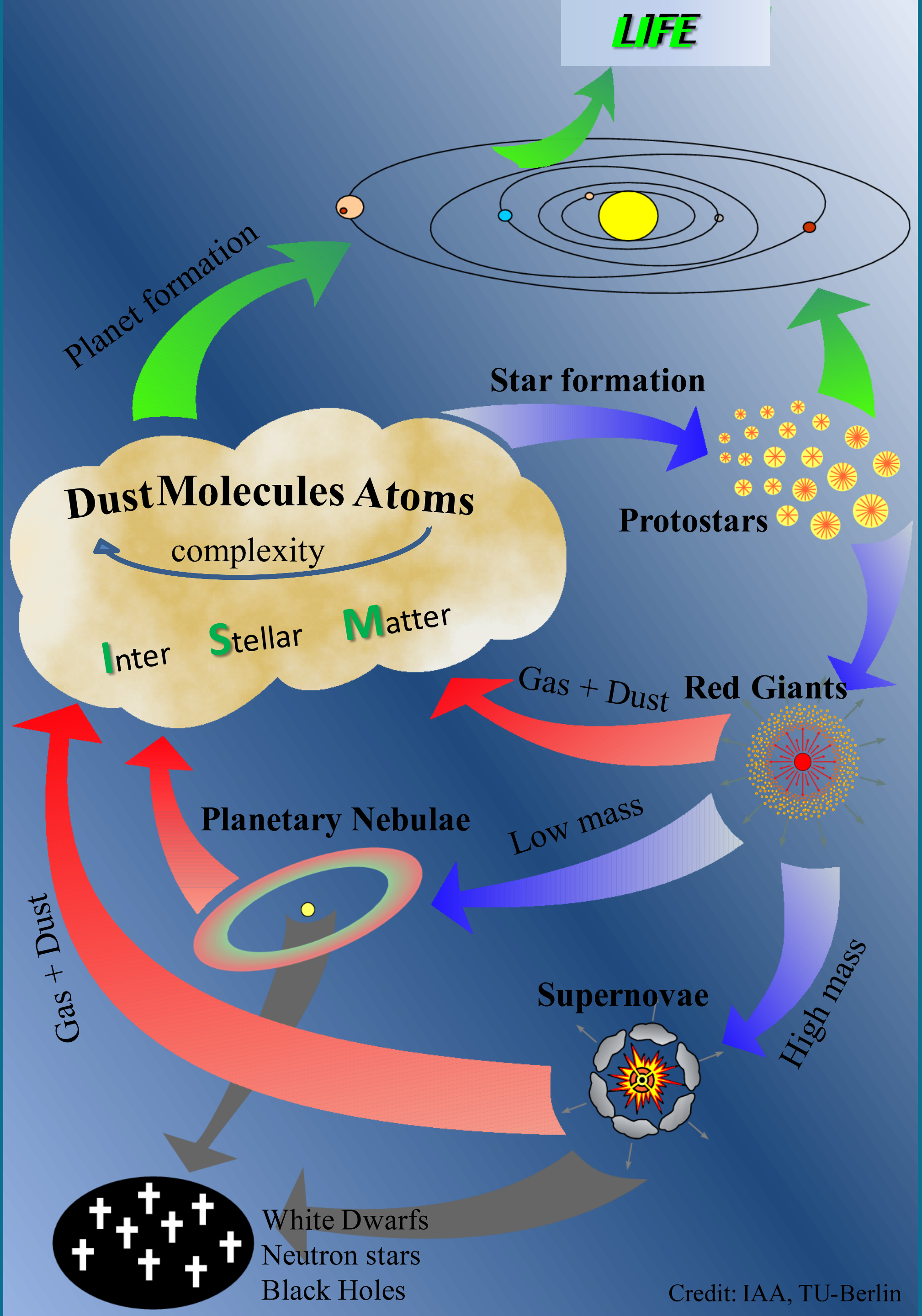


LIFE

Planet formation

Star formation

Dust Molecules Atoms

complexity

Inter Stellar Matter

Protostars

Gas + Dust

Red Giants

Planetary Nebulae

Low mass

Gas + Dust

Supernovae

High mass

White Dwarfs
Neutron stars
Black Holes

Credit: IAA, TU-Berlin

Necessary conditions for dust formation

- suitable chemistry => condensing species (high-T condensate)
- „low“ temperature => stable clusters
- „high“ density => growth to macroscopic grains

⇒ Stellar sources of interstellar dust

Asymptotic Giant Branch stars
Red Giant Branch stars, Red Supergiants
ejecta of Supernovae and Novae
Wolf-Rayet stars, RCrB stars

(also Brown Dwarfs, but the material is not injected to the ISM)

Two different approaches to describe dust formation

nucleation theory

Kinetic nucleation theory
  Critical cluster
Moment equations
=>

Possibility to construct self-consistent dust shell models

Ex: Gail, Gauger, Patzer, Sedlmayr, Winters, Woitke

Dorfi, Feuchtinger, Höfner

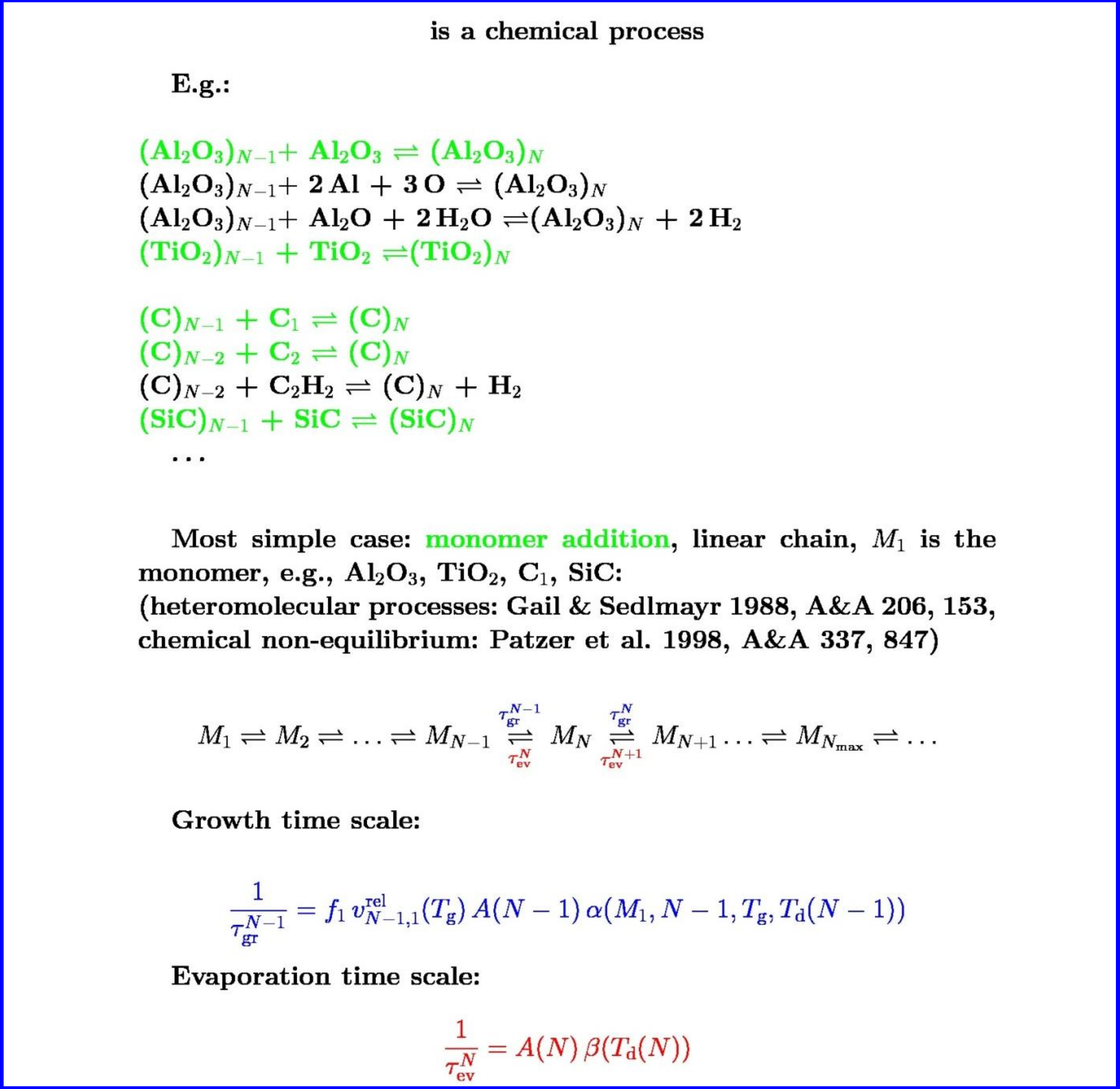
non-equilibrium chemistry

Chemical pathway
  Critical reaction
Rate network
=>

Possibility to construct complex non-equilibrium chemical models under prescribed thermodynamical conditions

Ex: Cherchneff, Gobrecht, Plane

Dust formation



is a chemical process

E.g.:

$(Al_2O_3)_{N-1} + Al_2O_3 \rightleftharpoons (Al_2O_3)_N$
$(Al_2O_3)_{N-1} + 2\,Al + 3\,O \rightleftharpoons (Al_2O_3)_N$
$(Al_2O_3)_{N-1} + Al_2O + 2\,H_2O \rightleftharpoons (Al_2O_3)_N + 2\,H_2$
$(TiO_2)_{N-1} + TiO_2 \rightleftharpoons (TiO_2)_N$

$(C)_{N-1} + C_1 \rightleftharpoons (C)_N$
$(C)_{N-2} + C_2 \rightleftharpoons (C)_N$
$(C)_{N-2} + C_2H_2 \rightleftharpoons (C)_N + H_2$
$(SiC)_{N-1} + SiC \rightleftharpoons (SiC)_N$
...

Most simple case: monomer addition, linear chain, M_1 is the monomer, e.g., Al_2O_3, TiO_2, C_1, SiC:
(heteromolecular processes: Gail & Sedlmayr 1988, A&A 206, 153, chemical non-equilibrium: Patzer et al. 1998, A&A 337, 847)

$$M_1 \rightleftharpoons M_2 \rightleftharpoons \ldots \rightleftharpoons M_{N-1} \underset{\tau_{\rm ev}^{N}}{\overset{\tau_{\rm gr}^{N-1}}{\rightleftharpoons}} M_N \underset{\tau_{\rm ev}^{N+1}}{\overset{\tau_{\rm gr}^{N}}{\rightleftharpoons}} M_{N+1} \ldots \rightleftharpoons M_{N_{\max}} \rightleftharpoons \ldots$$

Growth time scale:

$$\frac{1}{\tau_{\rm gr}^{N-1}} = f_1\, v_{N-1,1}^{\rm rel}(T_{\rm g})\, A(N-1)\, \alpha(M_1, N-1, T_{\rm g}, T_{\rm d}(N-1))$$

Evaporation time scale:

$$\frac{1}{\tau_{\rm ev}^{N}} = A(N)\, \beta(T_{\rm d}(N))$$

Stability

Thermodynamic equilibrium (phase equilibrium, thermal equilibrium ($T_\mathrm{g} = T_\mathrm{d}$), chemical equilibrium, denoted by $^\circ$):

Detailed balance

$$\frac{1}{\mathring{\tau}^{N}_{\mathrm{ev}}} = \frac{1}{\mathring{\tau}^{N-1}_{\mathrm{gr}}}$$

$$\Longrightarrow$$

$$\frac{1}{\tau^{N}_{\mathrm{ev}}} = \mathring{f}_1 \, \mathring{v}^{\mathrm{rel}}_{N-1,1}\,(T_\mathrm{d})\, A(N-1)\, \mathring{\alpha}\,(T_\mathrm{d}, T_\mathrm{d})$$

$$\Longrightarrow$$

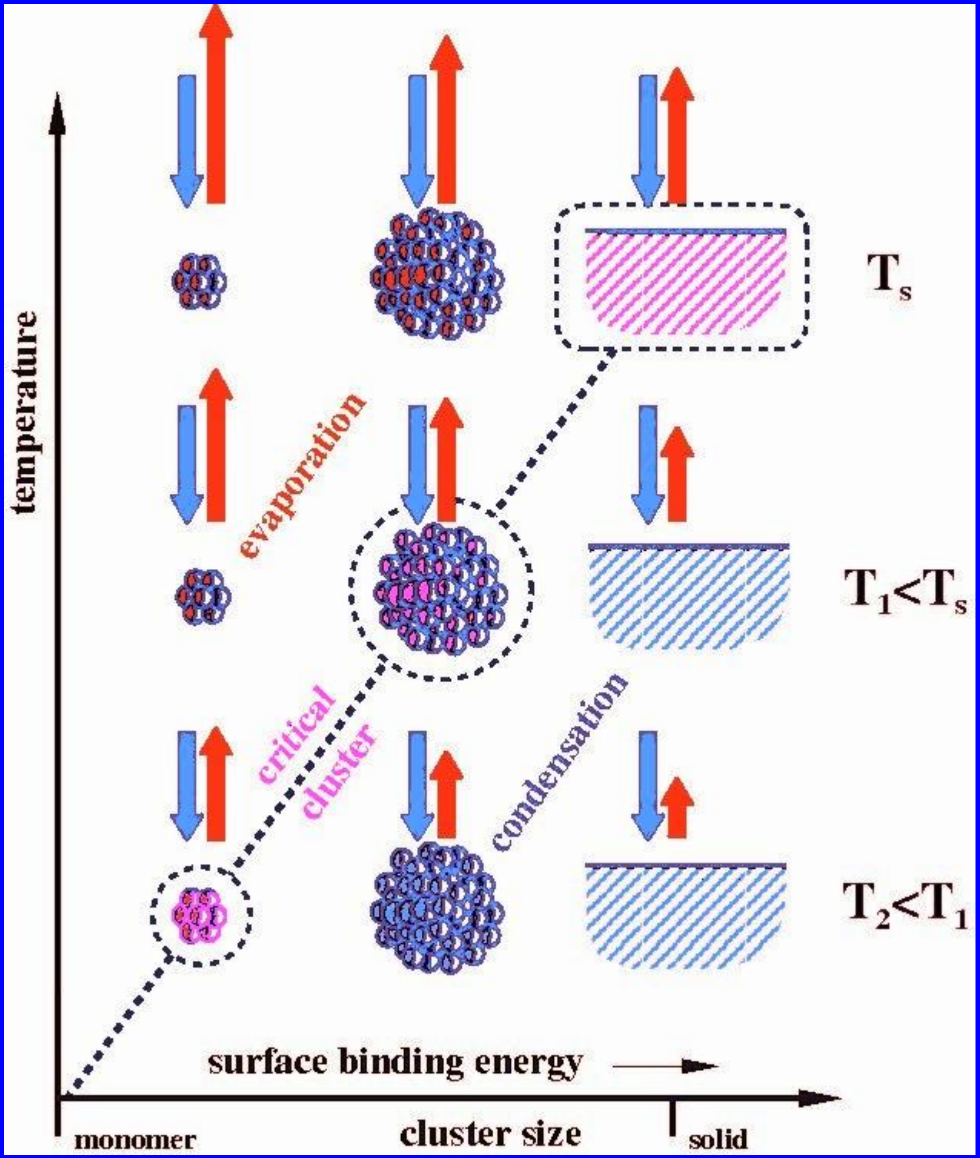
Net growth rate:

$$\begin{aligned}\frac{1}{\tau} = \frac{1}{\tau^{N-1}_{\mathrm{gr}}} - \frac{1}{\tau^{N}_{\mathrm{ev}}} &= \frac{1}{\tau^{N-1}_{\mathrm{gr}}}\left[1 - \frac{p_{\mathrm{vap}}(T_\mathrm{d})}{f_1\, kT_\mathrm{d}}\, \frac{\mathring{v}^{\mathrm{rel}}_{N-1,1}\,(T_\mathrm{d})}{v^{\mathrm{rel}}_{N-1,1}(T_\mathrm{g})}\, \frac{\mathring{\alpha}\,(T_\mathrm{d}, T_\mathrm{d})}{\alpha(T_\mathrm{g}, T_\mathrm{d})}\right] \\ &= \frac{1}{\tau^{N-1}_{\mathrm{gr}}}\left[1 - \frac{1}{S}\,\frac{1}{b_{\mathrm{therm}}}\,\frac{1}{b_{\mathrm{chem}}}\right]\end{aligned}$$

$$S = \frac{f_1^{\mathrm{CE}} kT_\mathrm{g}}{p_{\mathrm{vap}}(T_\mathrm{g})}, \qquad b_{\mathrm{therm}} = \frac{p_{\mathrm{vap}}(T_\mathrm{g})}{p_{\mathrm{vap}}(T_\mathrm{d})}\, \frac{T_\mathrm{g}}{T_\mathrm{d}}\, \frac{\mathring{v}^{\mathrm{rel}}_{N-1,1}\,(T_\mathrm{d})}{v^{\mathrm{rel}}_{N-1,1}(T_\mathrm{g})}\, \frac{\mathring{\alpha}\,(T_\mathrm{d}, T_\mathrm{d})}{\alpha(T_\mathrm{g}, T_\mathrm{d})}, \qquad b_{\mathrm{chem}} = \frac{f_1}{f_1^{\mathrm{CE}}}$$

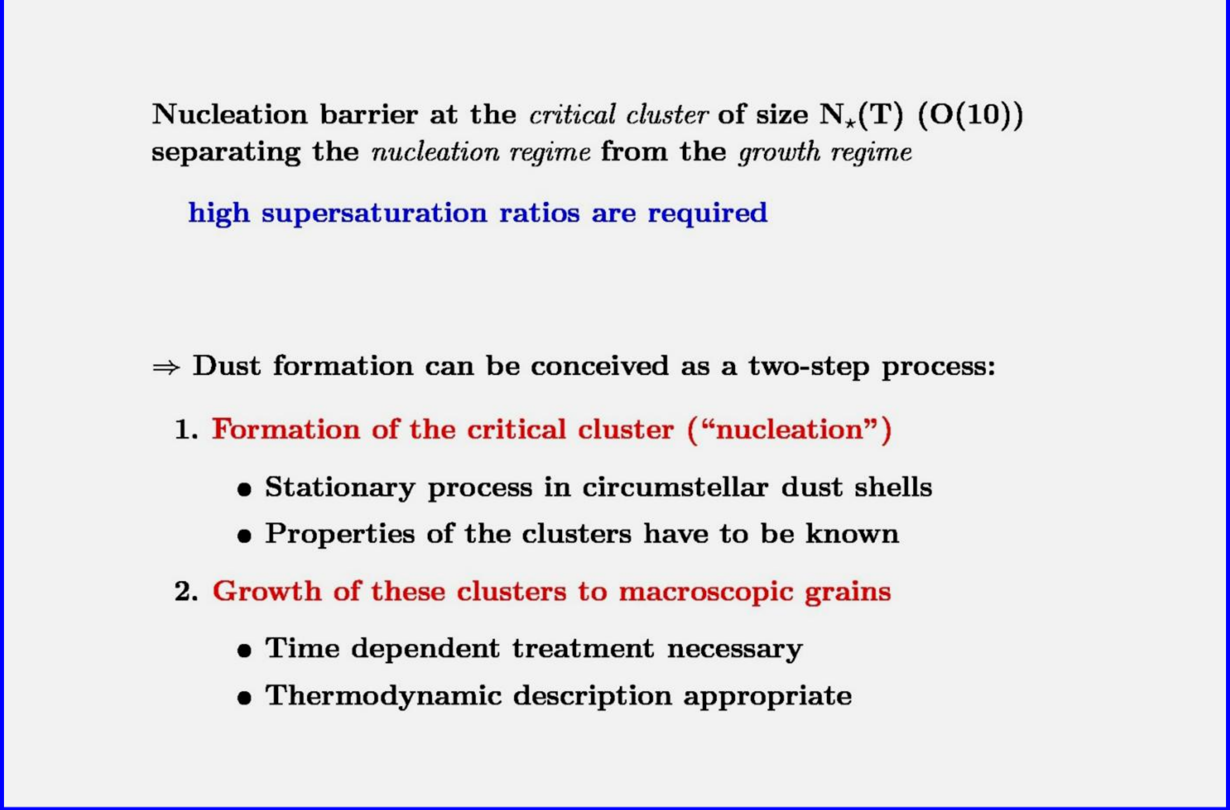
$$S\, b_{\mathrm{therm}}\, b_{\mathrm{chem}} \begin{cases} > 1 & : \ \text{net growth} \\ = 1 & : \ \text{stable} \\ < 1 & : \ \text{net evaporation} \end{cases}$$

Critical cluster



Credit: A. Goeres

Two-step process



Nucleation barrier at the *critical cluster* **of size $N_\star(T)$ ($O(10)$) separating the** *nucleation regime* **from the** *growth regime*

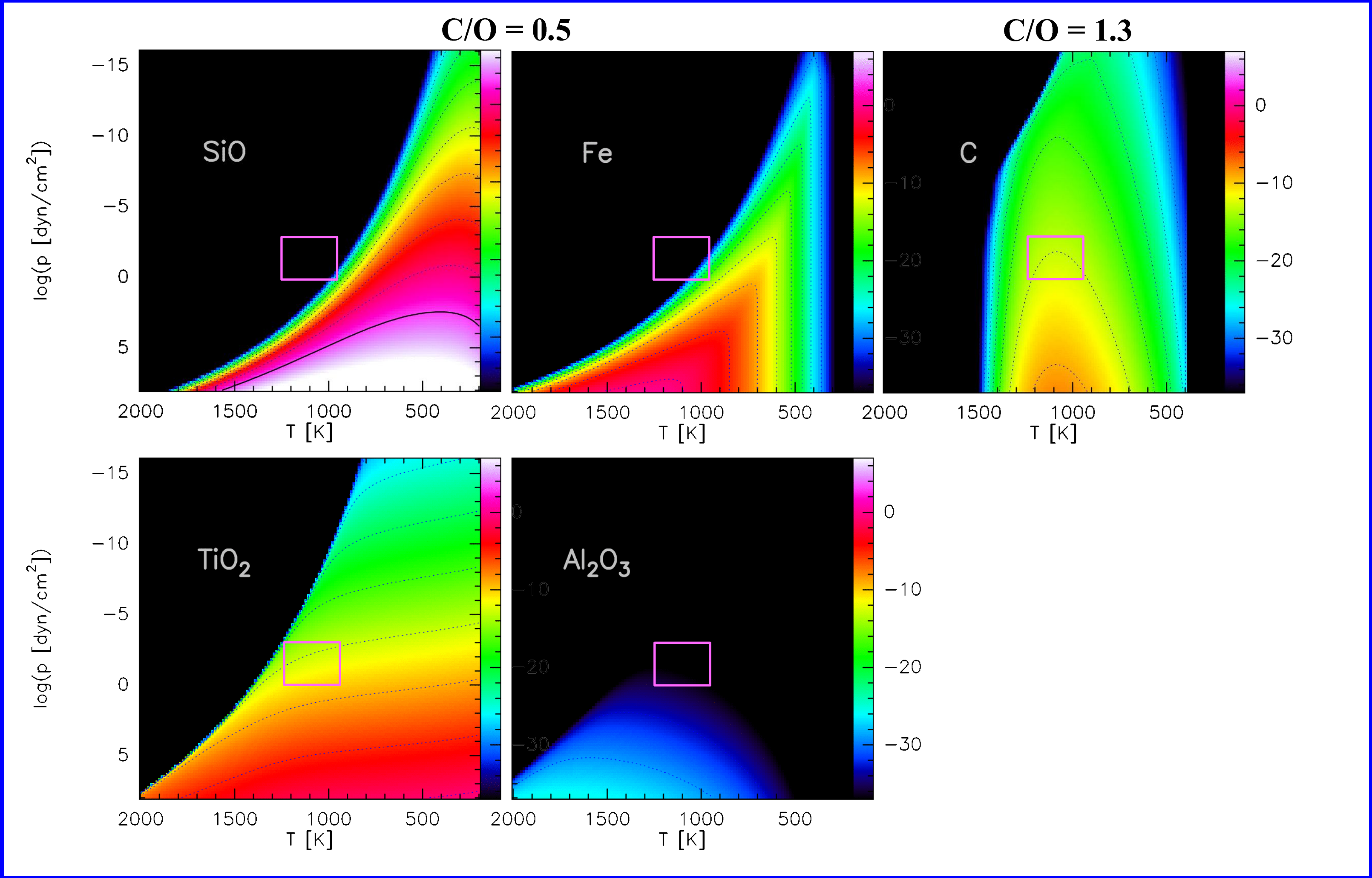
high supersaturation ratios are required

⇒ Dust formation can be conceived as a two-step process:

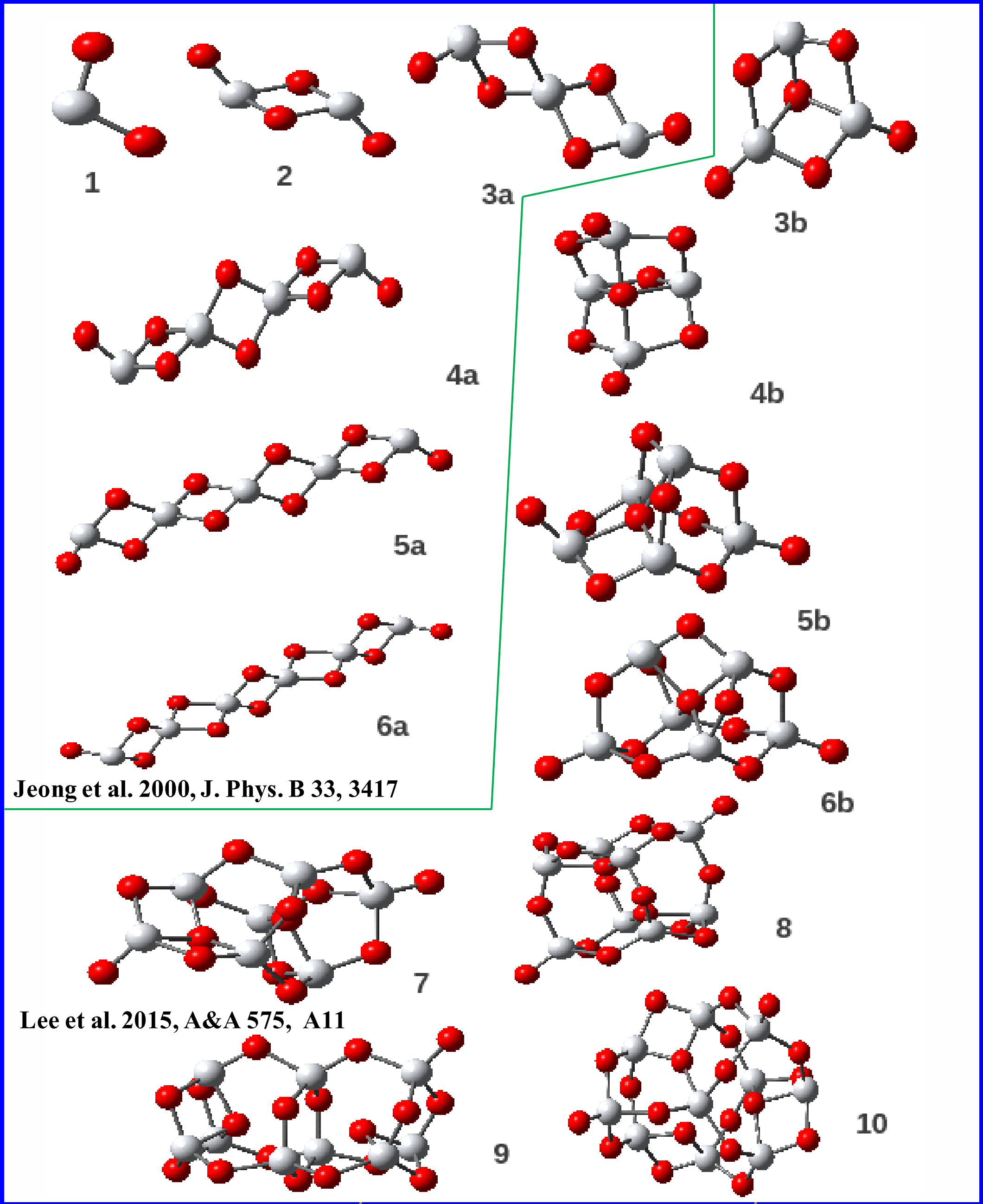
1. **Formation of the critical cluster ("nucleation")**
   - **Stationary process in circumstellar dust shells**
   - **Properties of the clusters have to be known**
2. **Growth of these clusters to macroscopic grains**
   - **Time dependent treatment necessary**
   - **Thermodynamic description appropriate**

Nucleation rates in the p-T plane

(=> chemical equilibrium)



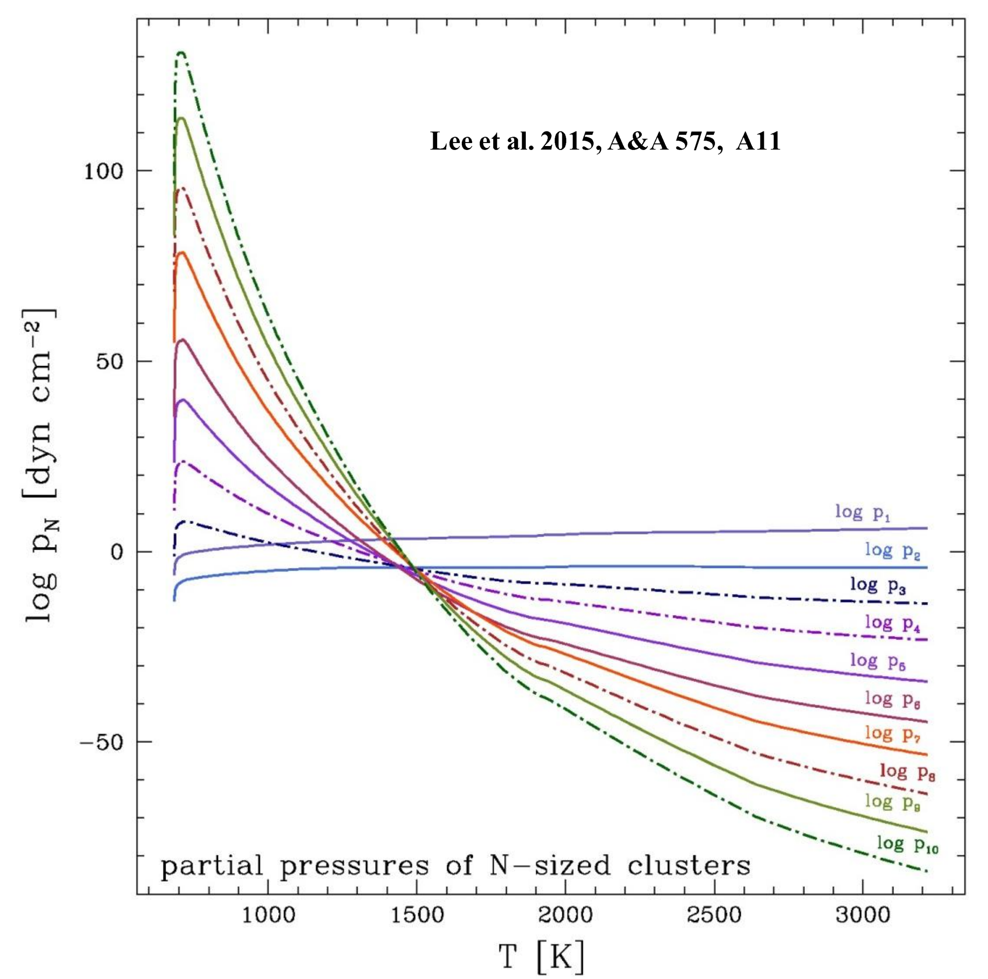
Equilibrium geometries of $(TiO_2)_N$ compounds



Jeong et al. 2000, J. Phys. B 33, 3417

Lee et al. 2015, A&A 575, A11

$(TiO_2)_N$ cluster distribution

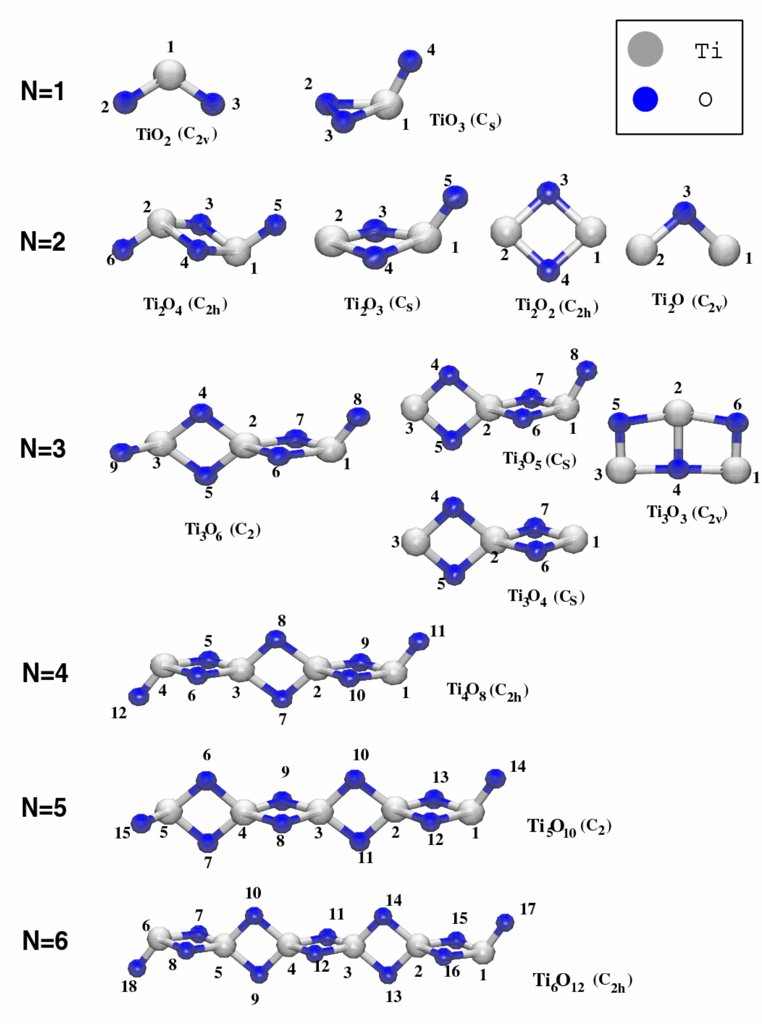


Lee et al. 2015, A&A 575, A11

TiO_2 in VY CMa

Equilibrium structures of Ti_xO_y systems

(Jeong et al. 2000, J.Phys.B 33, 3417)



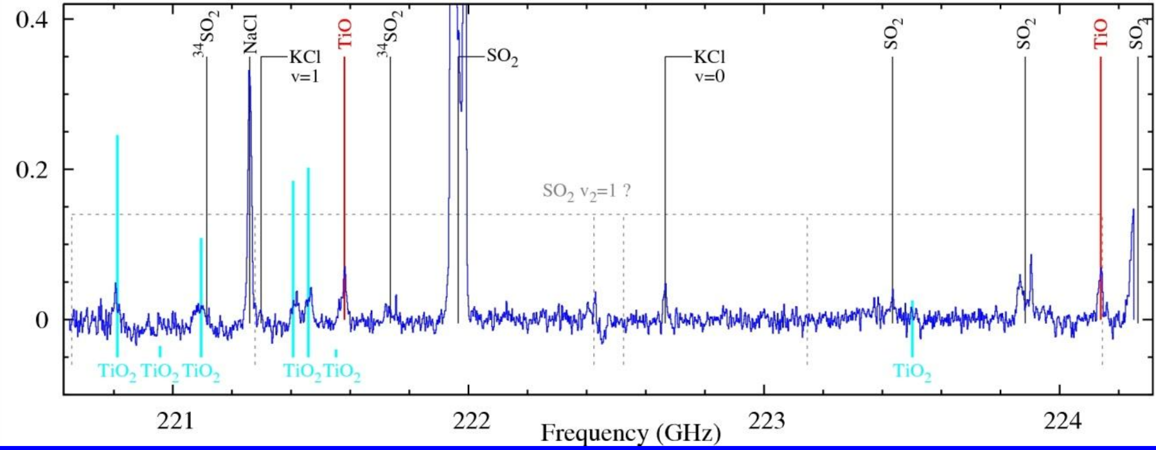
"…it is shown that titanium oxides, especially TiO_2 molecules, are the most probable candidates to form the primary condensates in circumstellar shells of M stars"

(Gail & Sedlmayr 1998, Faraday discussions 109, 303)

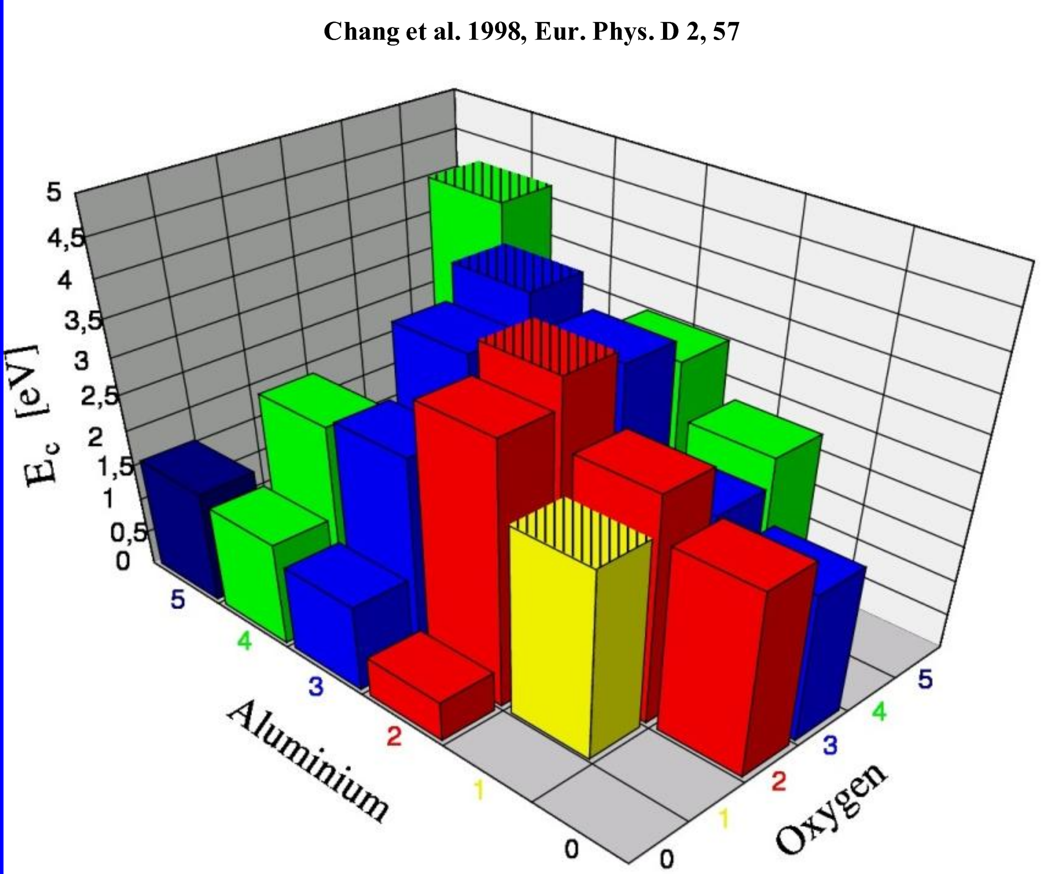
Mass-losing red supergiant VY CMa

First detection of TiO_2 in space (NOEMA/SMA)

(Kaminski et al. 2013, A&A 551, A113)

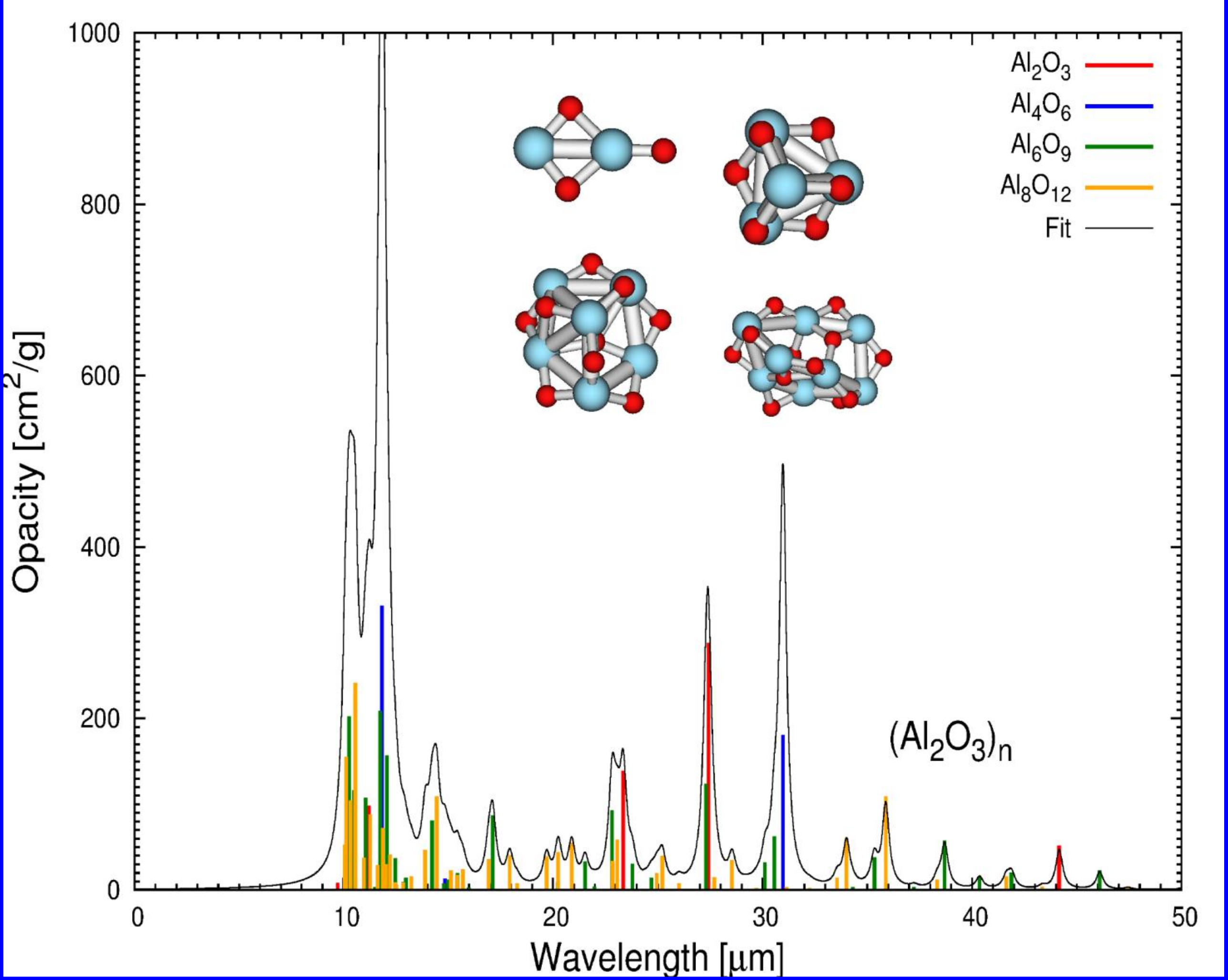


Binding energies of Al_xO_y compounds



Equilibrium geometries of $(Al_2O_3)_n$ clusters and vibrational transitions

(Decin et al. 2017, A&A 608, A55)

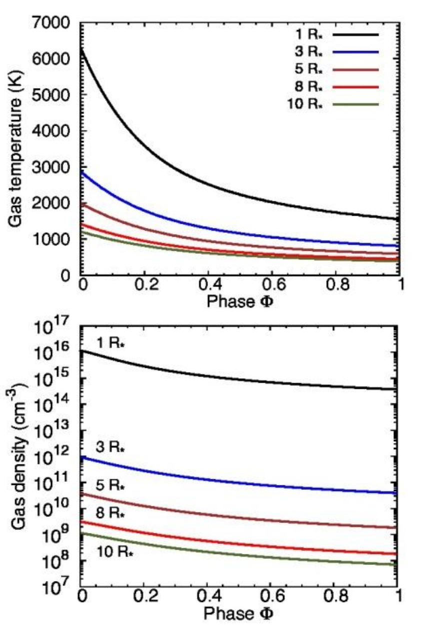


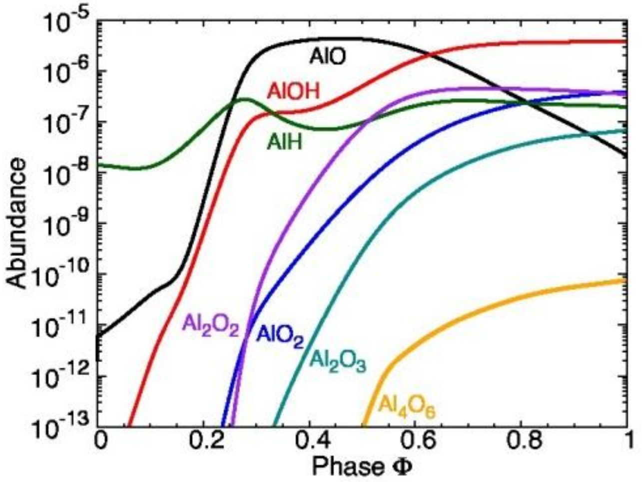
Non-equilibrium chemistry of AlO bearing species

at r = 1R$_*$

$$\begin{aligned}
&Al + OH &&\rightarrow AlO\\
&AlO + AlO + M &&\rightarrow Al_2O_2 + M\\
&Al_2O_2 + H_2O &&\rightarrow Al_2O_3 + H_2\\
&2\,Al_2O_3 + M &&\rightarrow (Al_2O_3)_2 + M
\end{aligned}$$

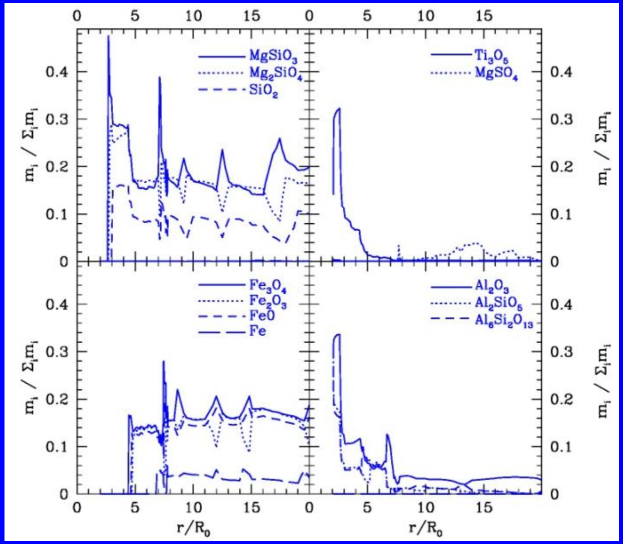
critical reaction





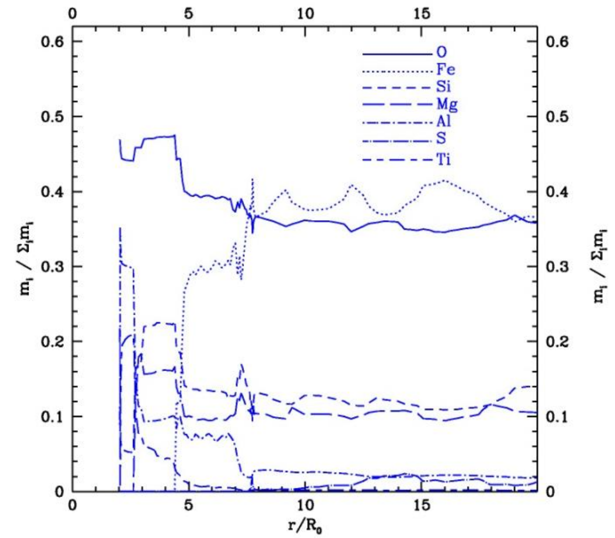
Gobrecht et al. 2016, A&A 585, A6

Condensates in an oxygen-rich model calculation



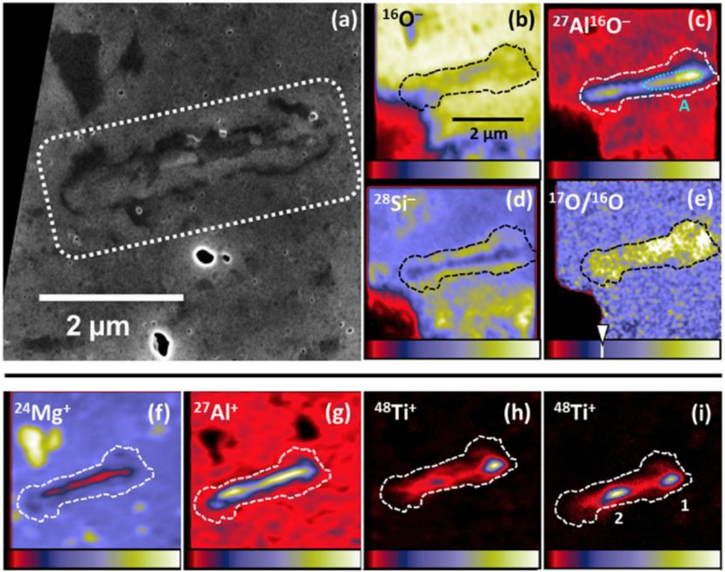
(Jeong et al. 2003, A&A 407, 191)

TiO_2 seeds,
Mantle growth by
Ti_xO_y, Al_xO_y,
$MgSiO_3$, Mg_2SiO_4
SiO_2, Fe_xO_y…



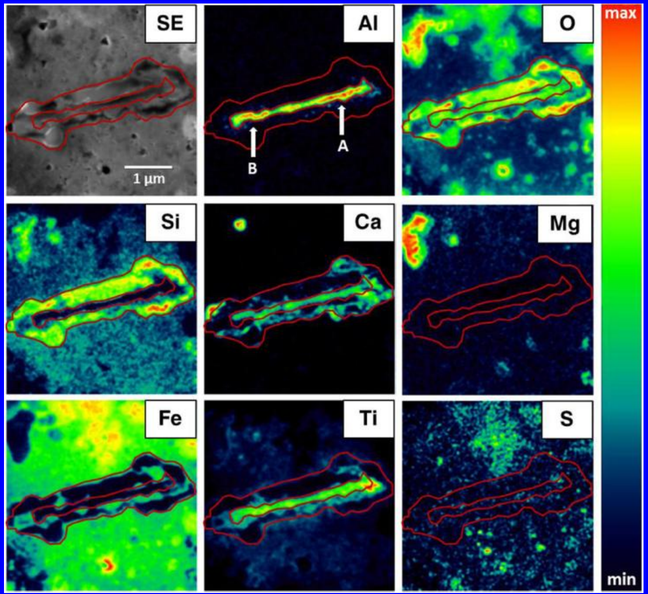
Presolar O-rich grain from Krymka LL3.2 chondrite

(Leitner et al. 2018, Geochim. Cosmochim. Acta 221, 255)



Core: O, Al, Ti,
Mantle: O, Si, Fe

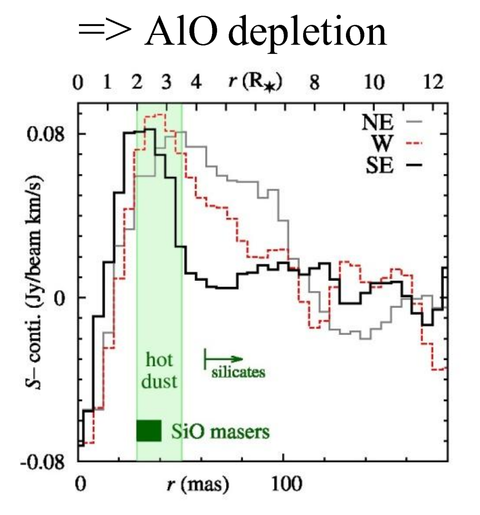
Core:
44% Al_2O_3, 44% TiO_2
In mantle only: Si, Fe

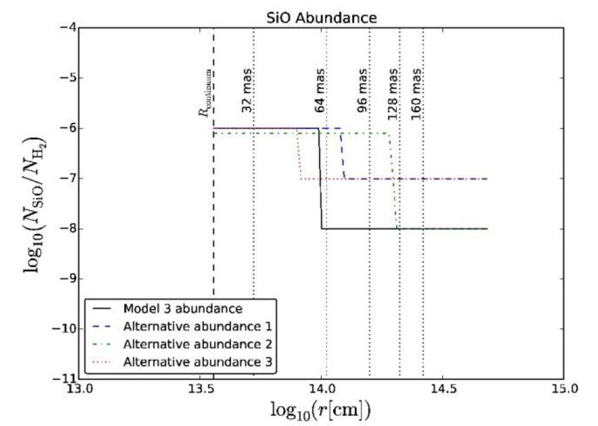


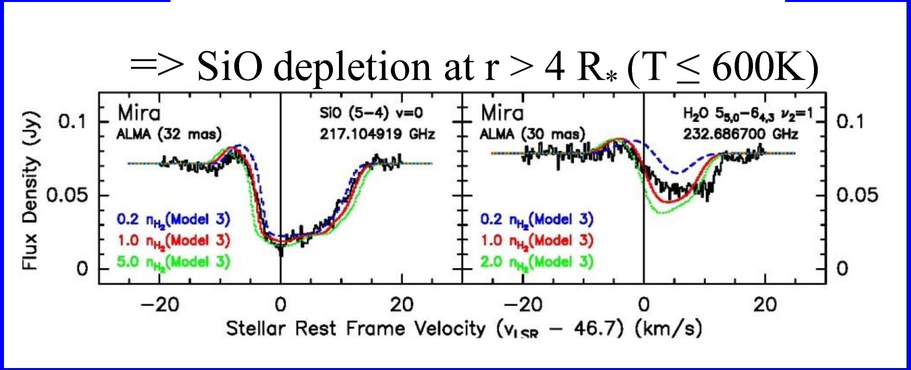
Observational study of dust formation in o Ceti

Wong et al. 2016, A&A 590, A127

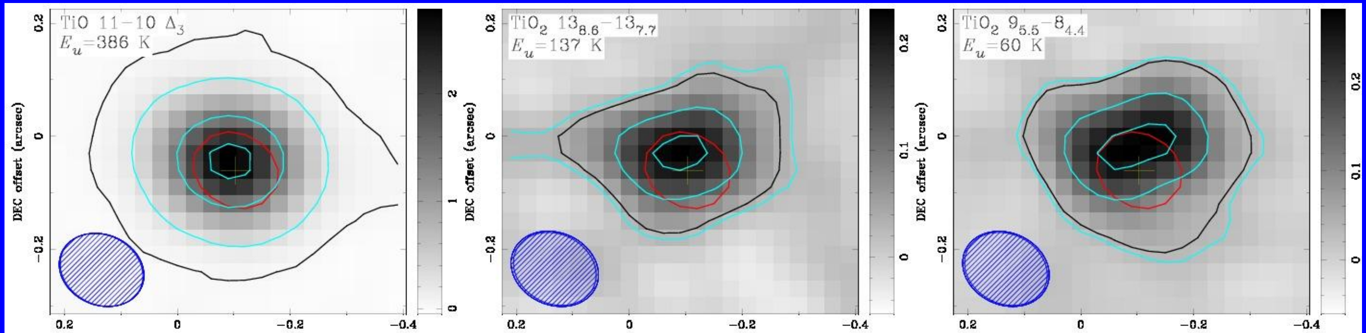
AlO(6-5): Kaminski et al. 2016, A&A 592, A42


=> AlO depletion



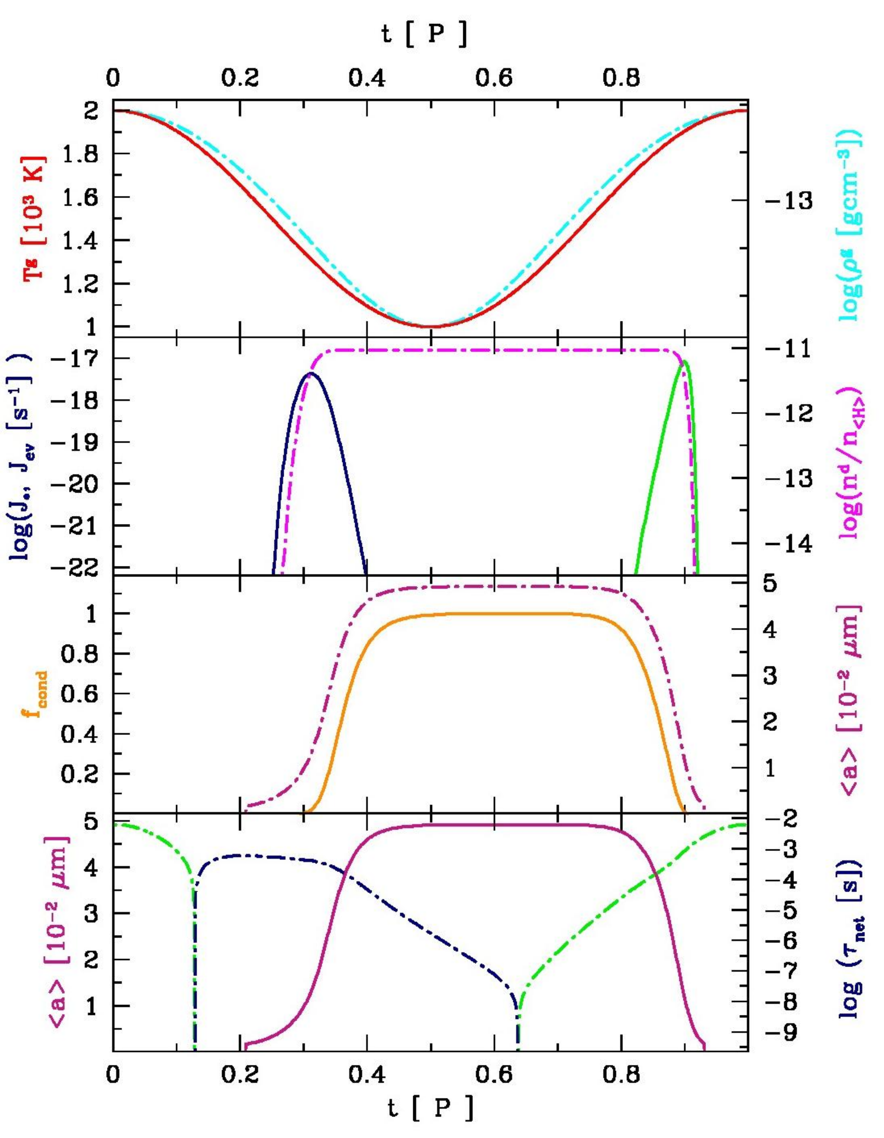

=> SiO depletion at r > 4 R* (T ≤ 600K)

Kaminski et al. 2017, A&A 599, A59

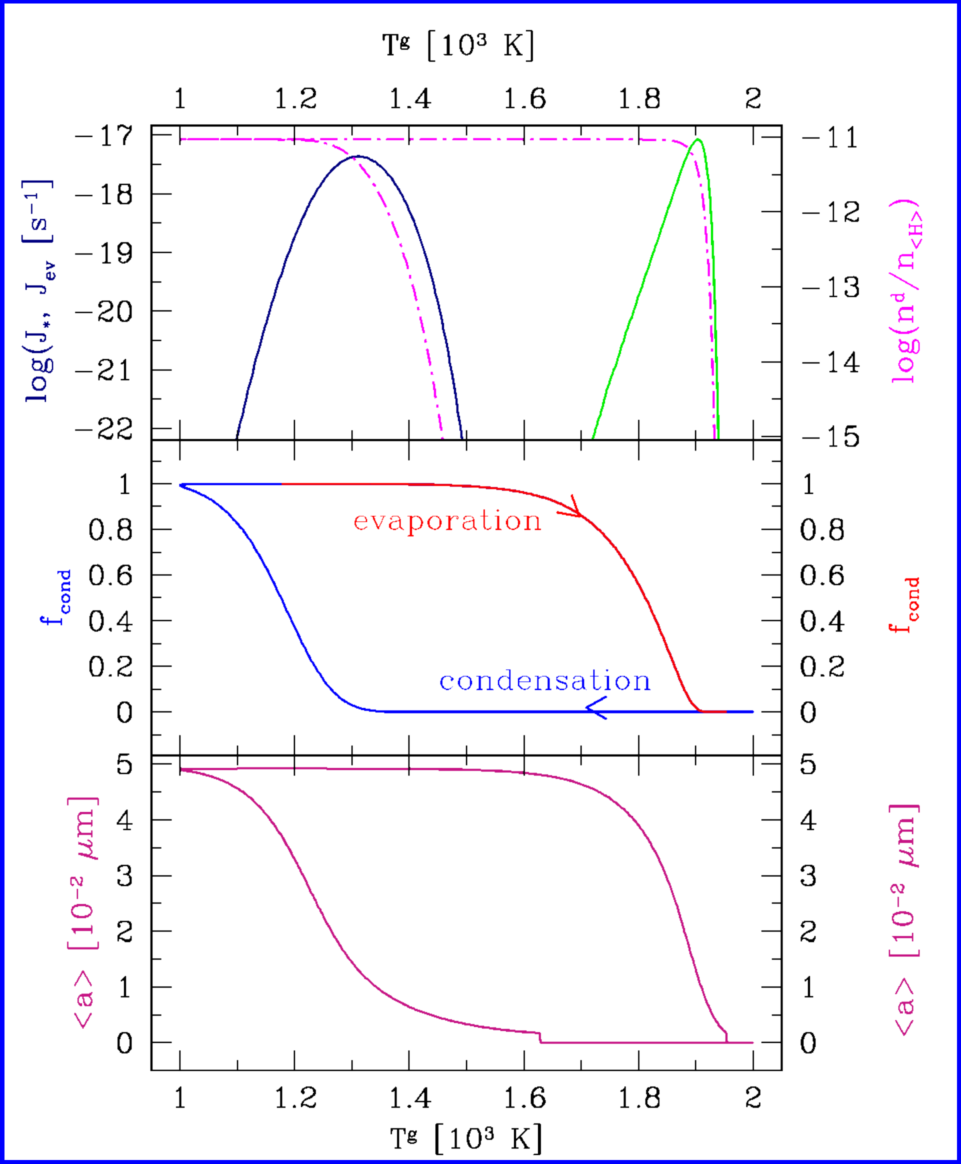


TiO_2 more extended than TiO => unlikely to be the first condensate!

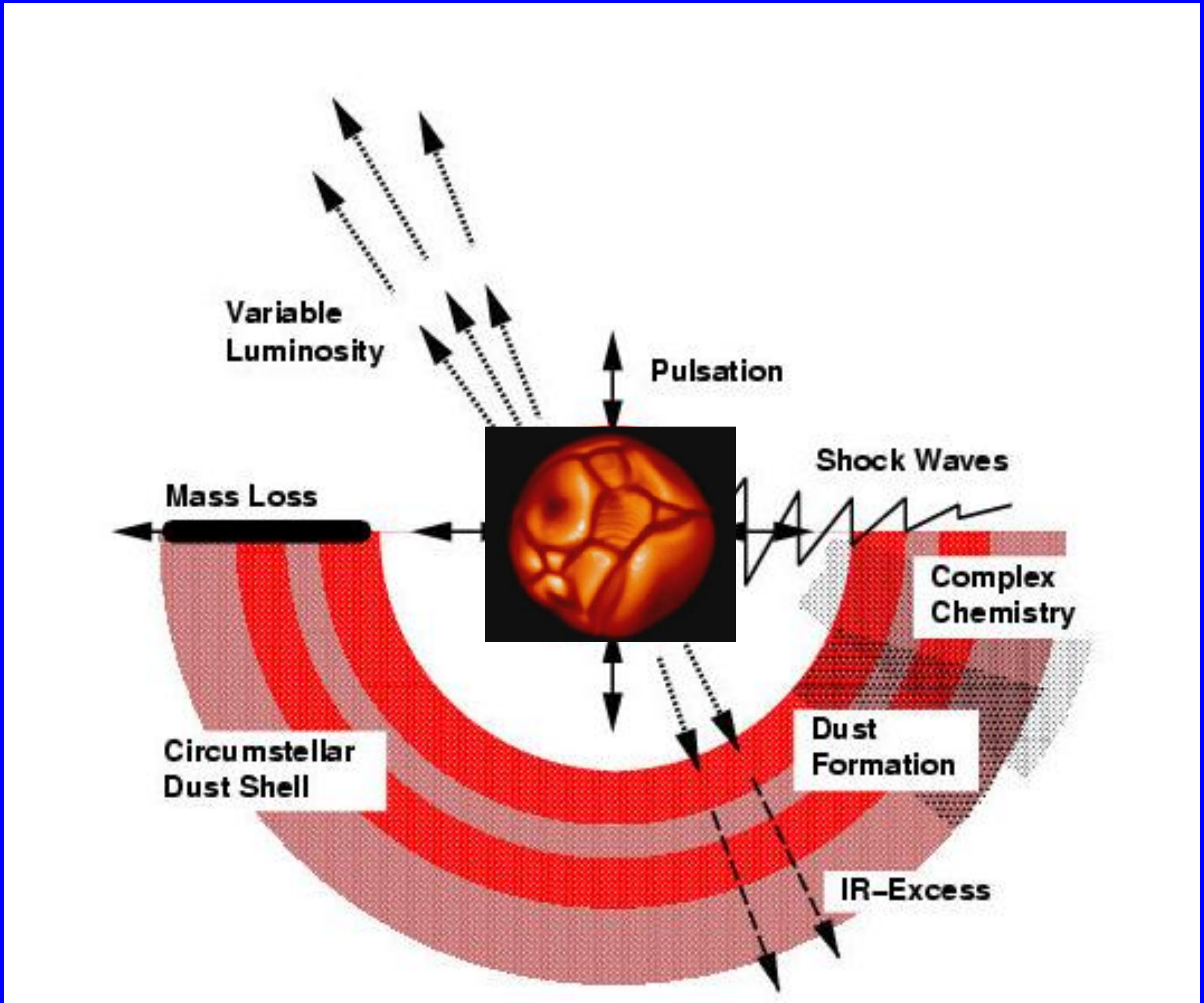
Carbon dust formation in a gas box with oscillating thermodynamic conditions



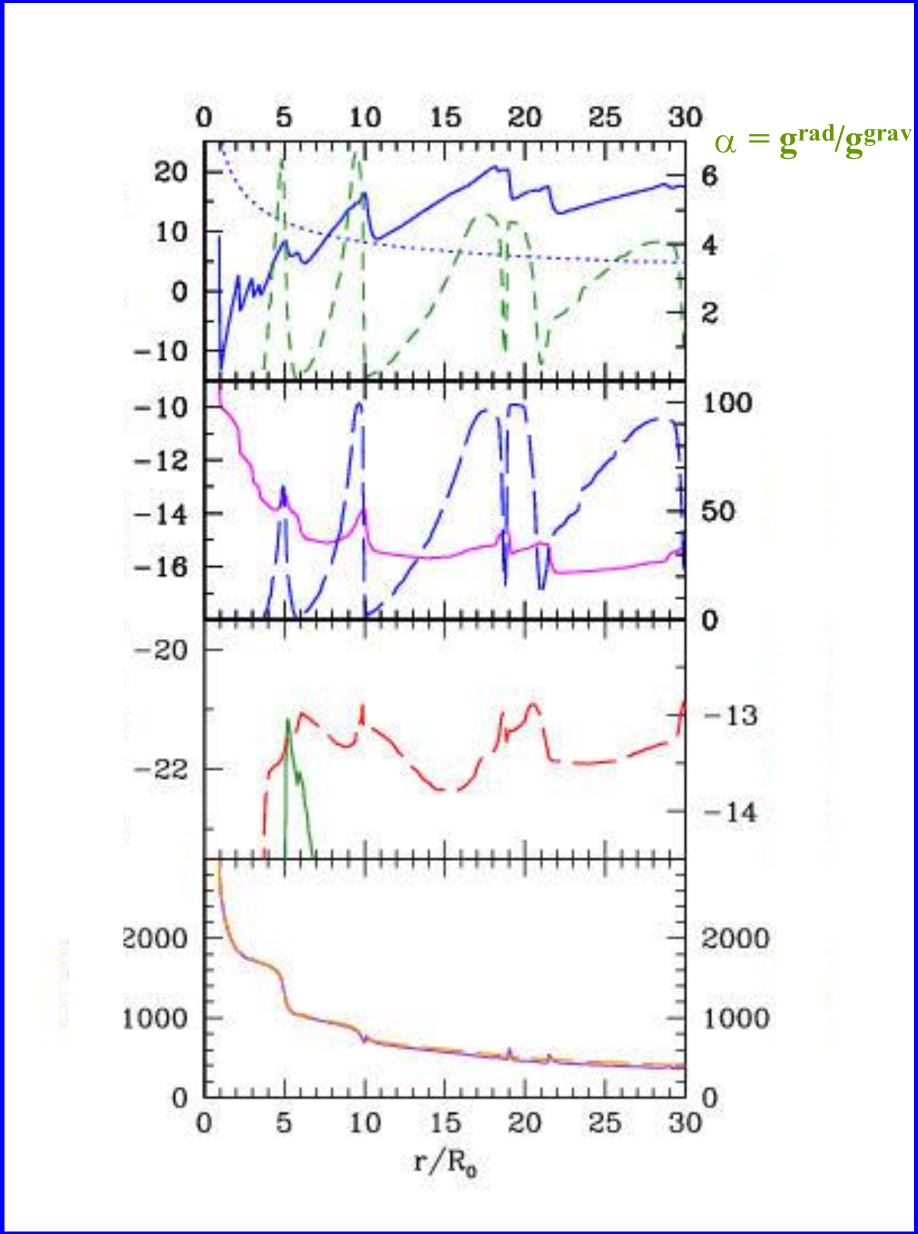
Carbon dust formation in a gas box
Supercooling => hysteresis



Scenario of a dust forming circumstellar shell



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

$\Delta v_p = 8$ km/s

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

$v_{exp} = 17.3$ km/s

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

2D carbon-rich models:
Woitke 2006, A&A 452, 537

Summary and conclusions

Two different physical descriptions of the astrophysical dust formation problem are at hand
The required input data start to become available

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

Chemical non-equilibrium calculations start to reproduce observed molecular abundances
Both approaches seem ready to be combined!