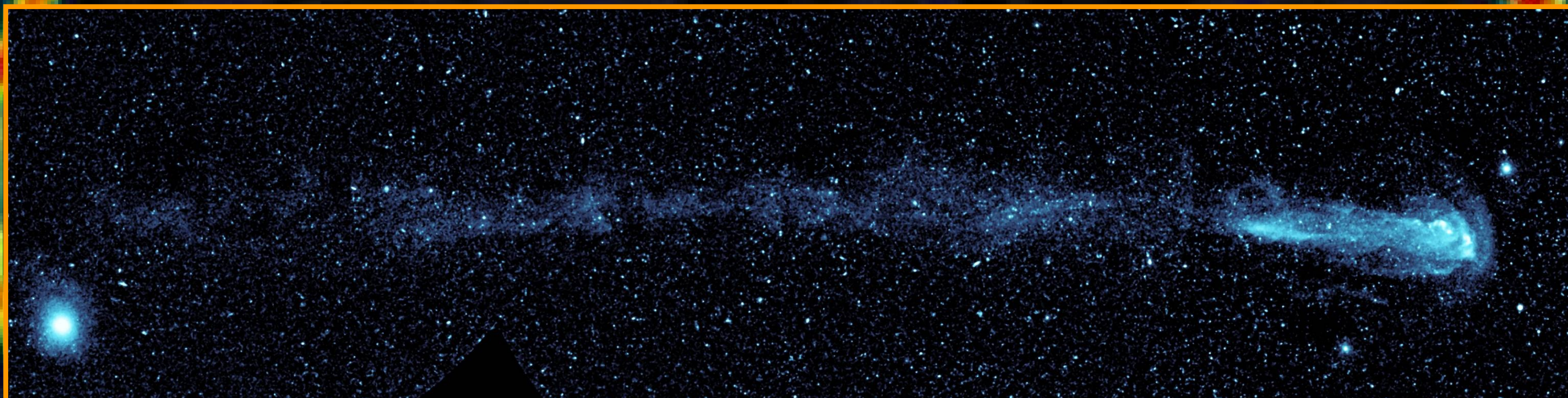
Late Stages of Stellar Evolution

Low to Intermediate Mass Stars

Section 6: Mass Loss

AGB Stars Lose Mass

- Really? Well, yes!
- Remember Mira? In the UV (Galex) it looks like this:

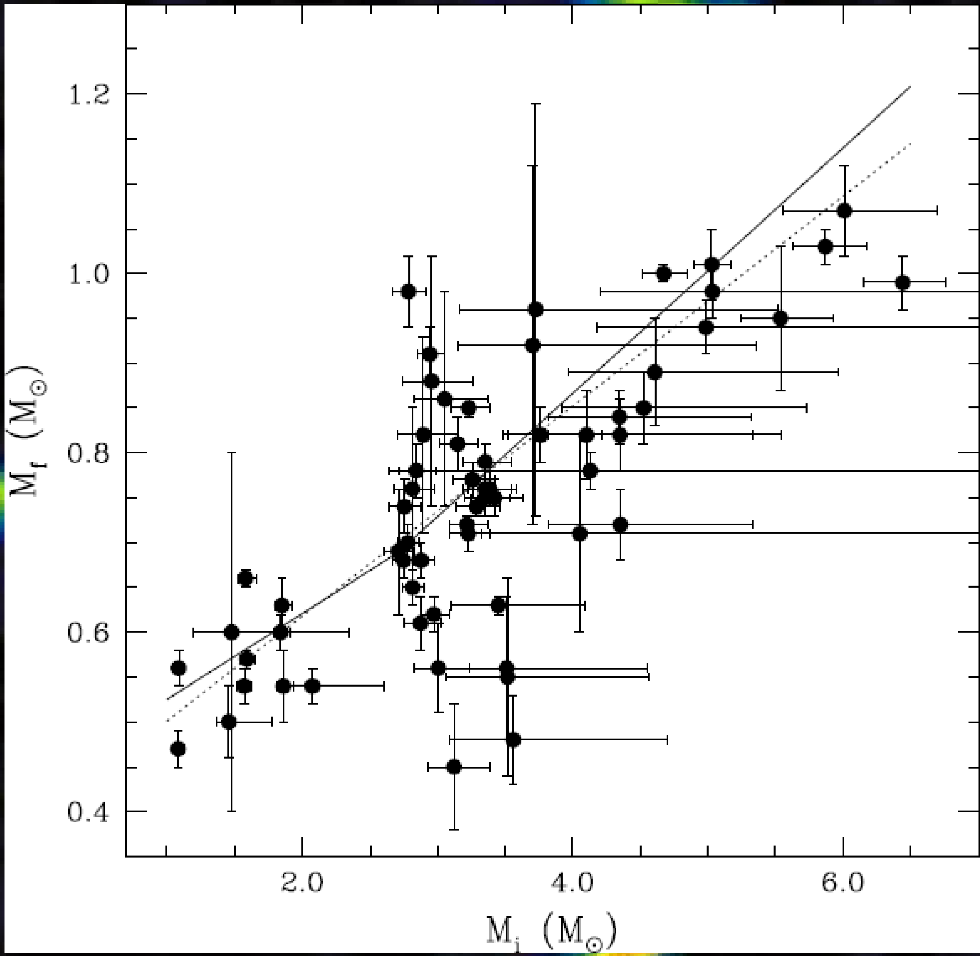


$2^\circ \approx 4$ pc

Consistent with previous mass loss estimates of $3\times10^{-7}\ M_\odot$/yr and a velocity of 5 km/s. Age: 450,000 years (from simulations).

Initial Final Mass Relation

- From the point of view of stellar evolution, we want to know the total amount of mass loss.
- Or: if we start the MS with 1 $M_\odot$, what will be the mass of the final WD?
- This is known as the initial-final mass relation (IFMR).
- Measured from WD populations in (open) clusters.



Williams (2006)
Catalan et al. (2008)

Mass Loss Recipes

- Reimers (1975):

$$\dot{M}_{\mathrm{Reimers}} = 4 \times 10^{-13} \eta \frac{(L/L_\odot)(R/R_\odot)}{(M/M_\odot)} \qquad M_\odot \ \mathrm{yr}^{-1}$$

- Blöcker (1993):

$$\dot{M}_{\mathrm{Bl}} = 4.83 \times 10^{-9} \left(\frac{M}{M_\odot}\right)^{-2.1} \left(\frac{L}{L_\odot}\right)^{2.7} \dot{M}_{\mathrm{Reimers}}$$

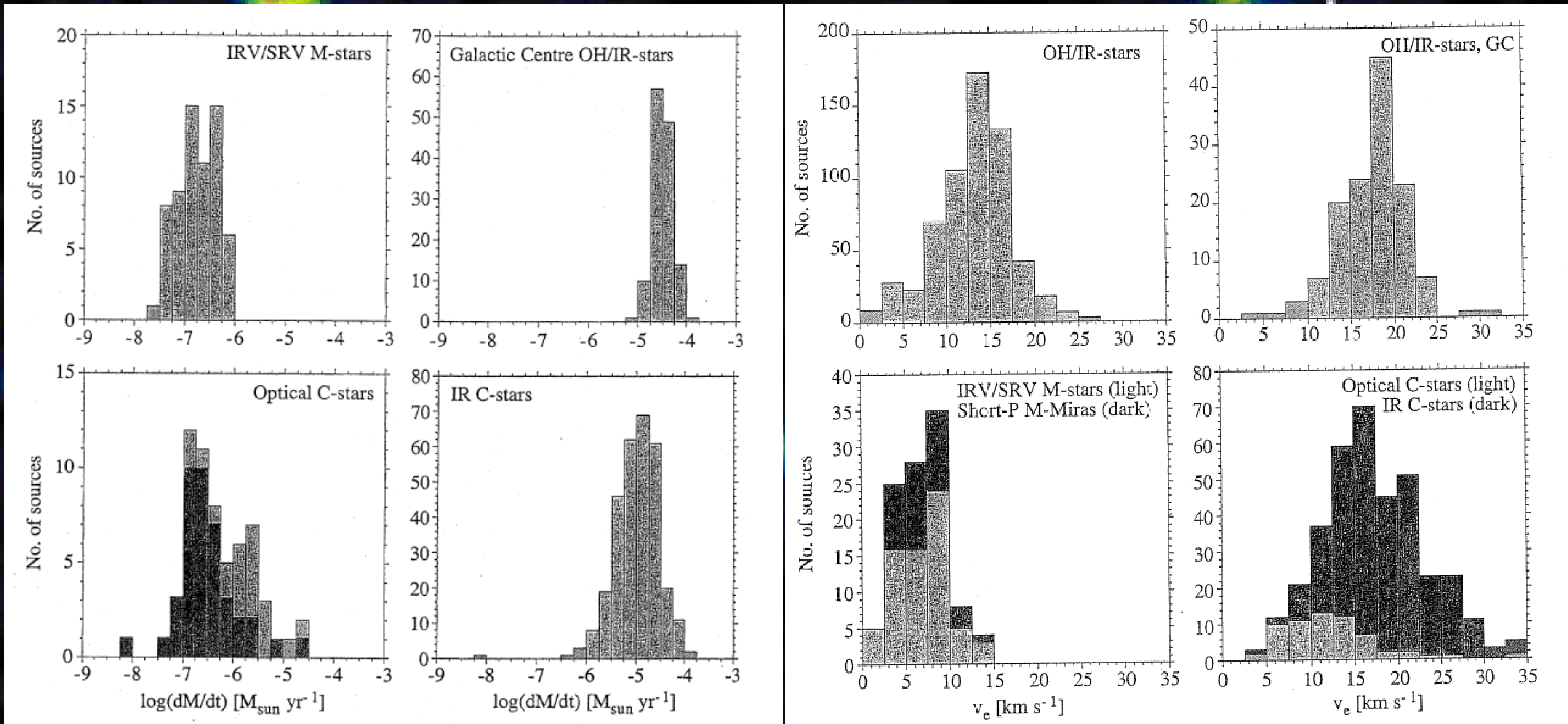
- Vassiliadis & Wood (1993):

$$\dot{M}_{\mathrm{VW}} = \min(\dot{M}_{\mathrm{radpres}}, \dot{M}_{\mathrm{superwind}})$$

$$\dot{M}_{\mathrm{radpres}} = \frac{L/c}{v_{\mathrm{exp}}}, \qquad \mathrm{with} \quad v_{\mathrm{exp}} = -13.5 + 0.056\Pi(\mathrm{days})$$

$$\log_{10} \dot{M}_{\mathrm{superwind}} = -11.4 + 0.0123\Pi(\mathrm{days})$$

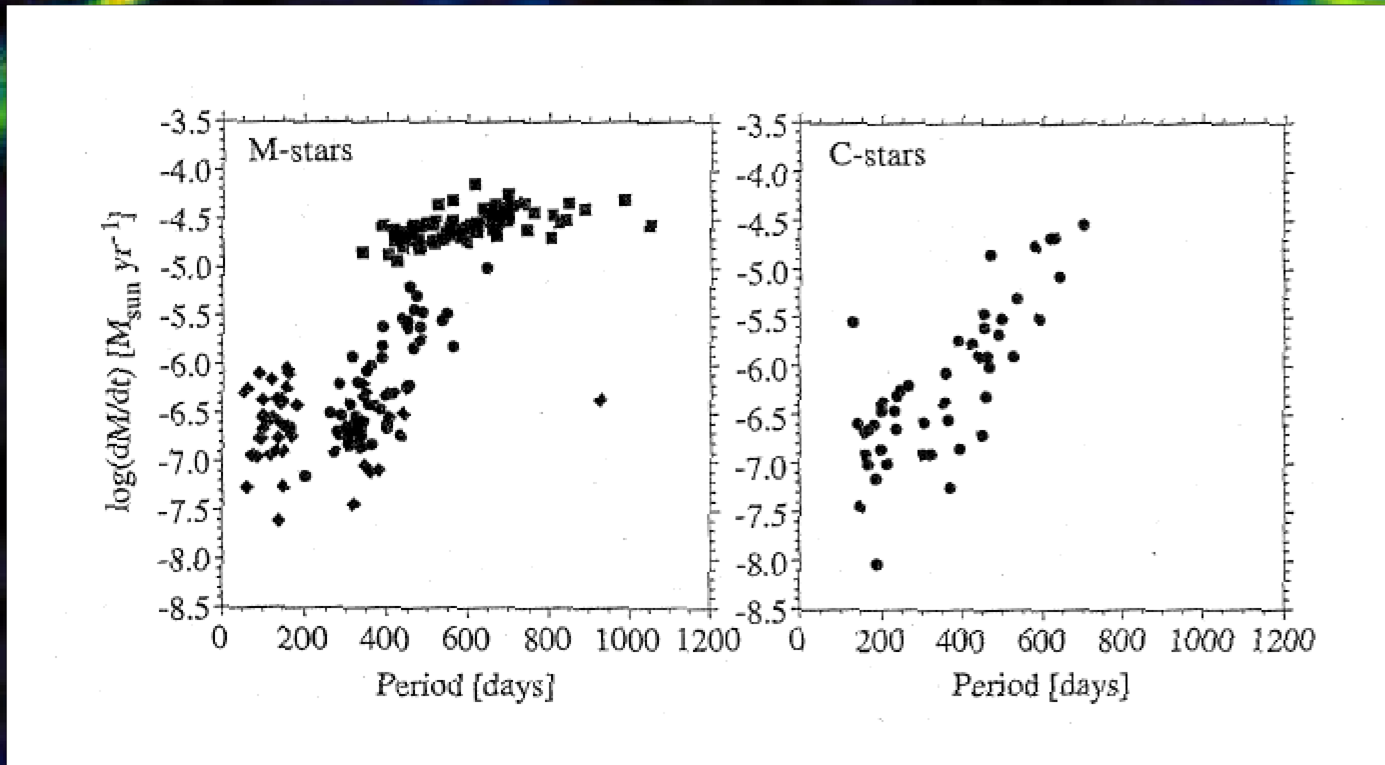
Mass Loss Measurements



Mass loss rates

Velocities

Mass Loss and Pulsations

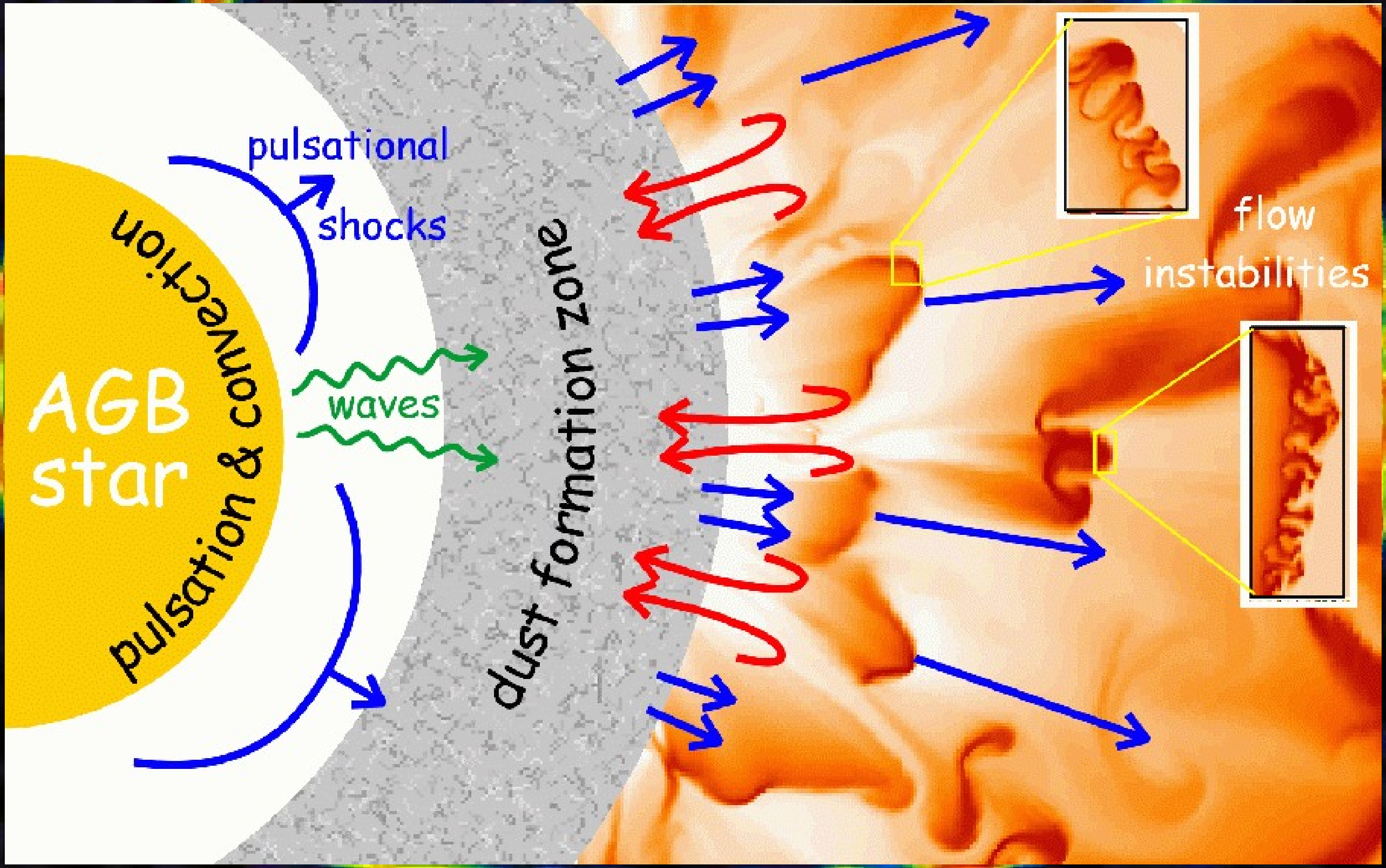


- Correlation between Π and $\dot{M}$ exists, but does not look simple.

Stellar Wind Theory

- The mass loss from AGB stars is characterized by high mass loss rates and low velocity, which has been difficult to reproduce.
- After the work of Bowen (1988) the idea that AGB winds are driven by radiation pressure on dust forming in a pulsating atmosphere, has become accepted.
- The modelling has been refined since then and has been successful in explaining typical AGB winds, but it is still not able to give a fully consistent theory.

Schematic Picture



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Complexity of Mass Loss Modelling

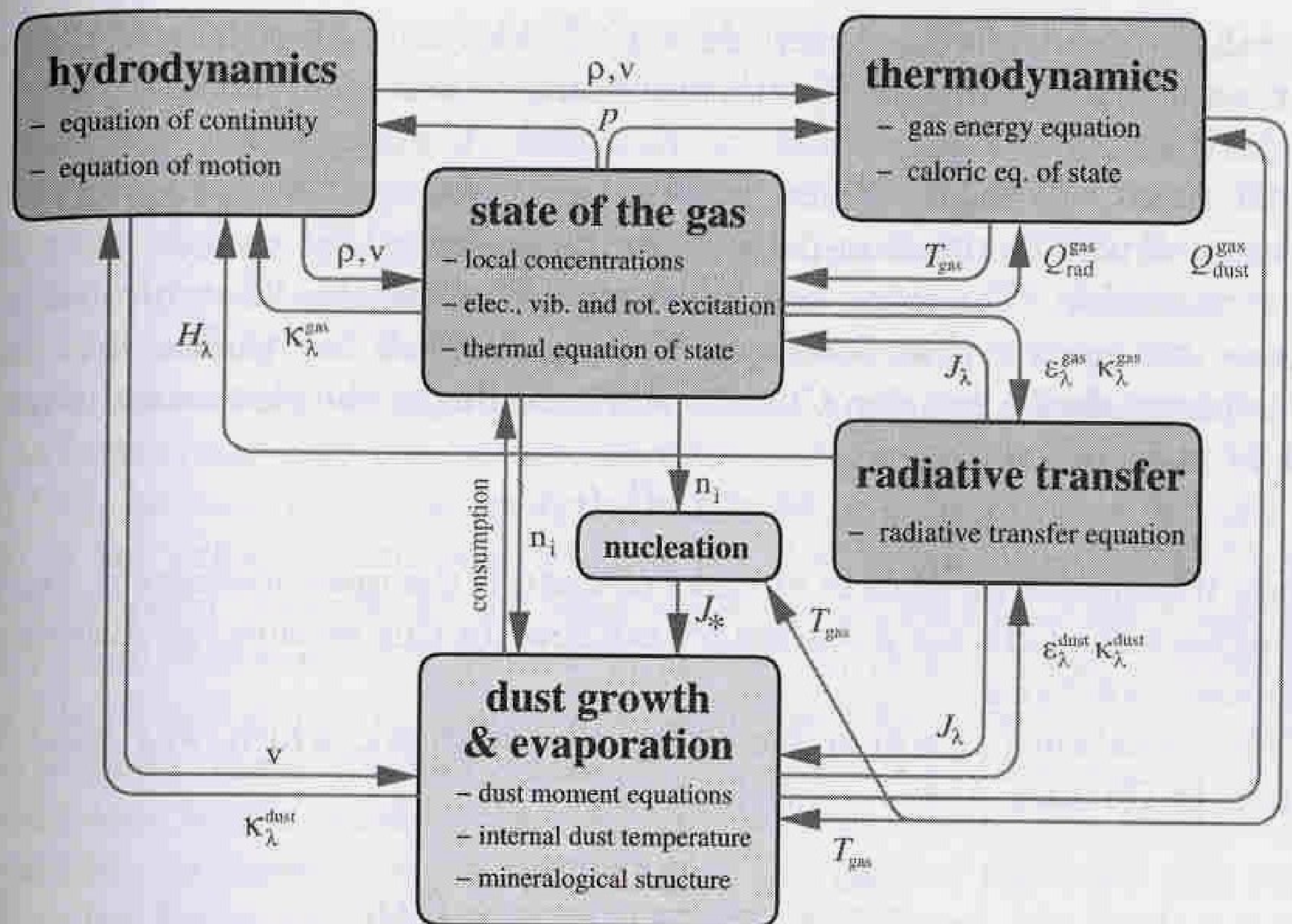


Fig. 6.2. Schematic overview of the interactions between the physical and chemical processes in the dust-forming AGB CSE. From [76]

Hydrodynamics

- Mass conservation (steady): $\dot{M} = 4\pi r^2 \rho v\,,$
- Momentum conservation (steady): $v\dfrac{\mathrm{d}v}{\mathrm{d}r} = -\dfrac{1}{\rho}\dfrac{\mathrm{d}p}{\mathrm{d}r} - \dfrac{GM}{r^2} + f(r)$
- Energy: assume an isothermal gas

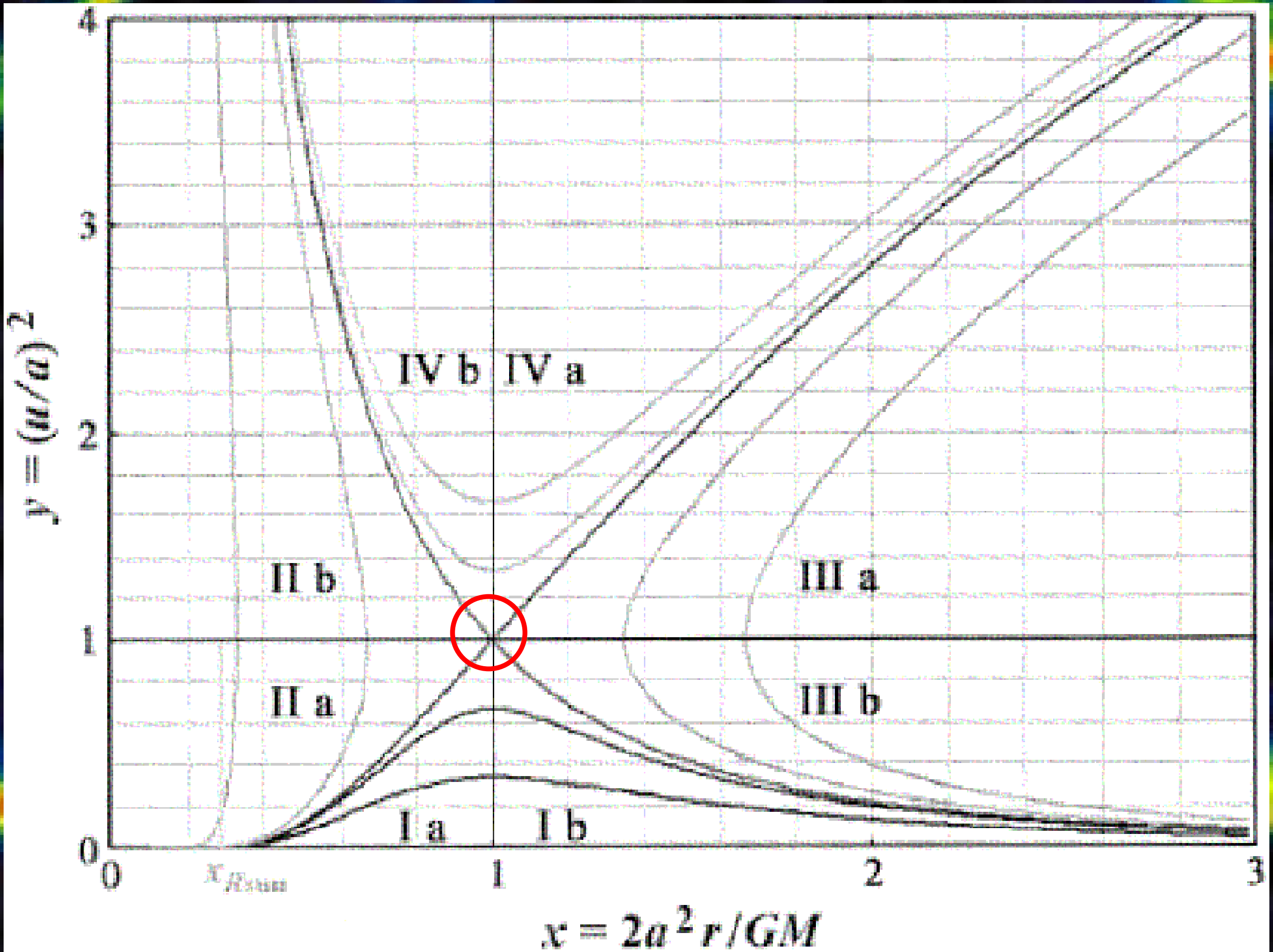
- From this the wind equation:

$$\frac{\mathrm{d}v}{\mathrm{d}r} = \frac{v}{v^2 - \vec{c}_{\mathrm{s}}^{\,2}}\left(\frac{2\vec{c}_{\mathrm{s}}^{\,2}}{r} - \frac{\mathrm{d}\vec{c}_{\mathrm{s}}^{\,2}}{\mathrm{d}r} - \frac{GM}{r^2} + f(r)\right)$$

- Critical point when $v=c_s$.

- For *f(r)* ≈ 0, only weak mass loss (Sun: $10^{-14}\ M_{\odot}\,\mathrm{yr}^{-1}$).

Stellar Wind Diagram



Applying the Force

- When there is a force, the critical point moves from $r_c = GM/2c_s^2$ to $r_c = \frac{GM}{2\bar{c}_s^2} - \frac{f(r_c) r_c^2}{2\bar{c}_s^2}$
- Since at $r = r_c$ we have $v = c_s$, and $\dot{M} = 4\pi r^2 \rho v$, the density at the critical sets the mass loss rate.
- If the critical point moves in (*$f(r_c) > 0$*), the mass loss rate will increase.
- However, if a force is applied in the region $r > r_c$, the mass loss rate will *not* go up. Instead the wind will acquire a higher velocity.

Three Wind Regions

$r<r_c$	$r=r_c$	$r>r_c$
Atmosphere-like Solution: Exponential Atmosphere ∂p/∂r term dominates		Wind-like Solution: Power laws ∂p/∂r term unimportant

$$\rho(r) = \rho_0 \exp\left\{-\frac{r-r_0}{H}\frac{r_0}{r}\right\}$$

$$H = \frac{c_s^2}{GM} r_0^2$$

Hydrostatic atmosphere

If force has r^{-2} behaviour:

$$r_c(\Gamma) = \frac{GM(1-\Gamma)}{2\bar{c}_s^2}$$

Scale Height Problem

- For a hydrostatic atmosphere solution, the shift of the critical point is not enough.
- $M=1\ M_\odot$, $R_*=300\ R_\odot$, $T_{eff}=2500$ K $\rightarrow$ $H/R_*=0.05$
- Even $\Gamma=0.5$ gives mass loss rates $10^{-16}\ M_\odot yr^{-1}$.

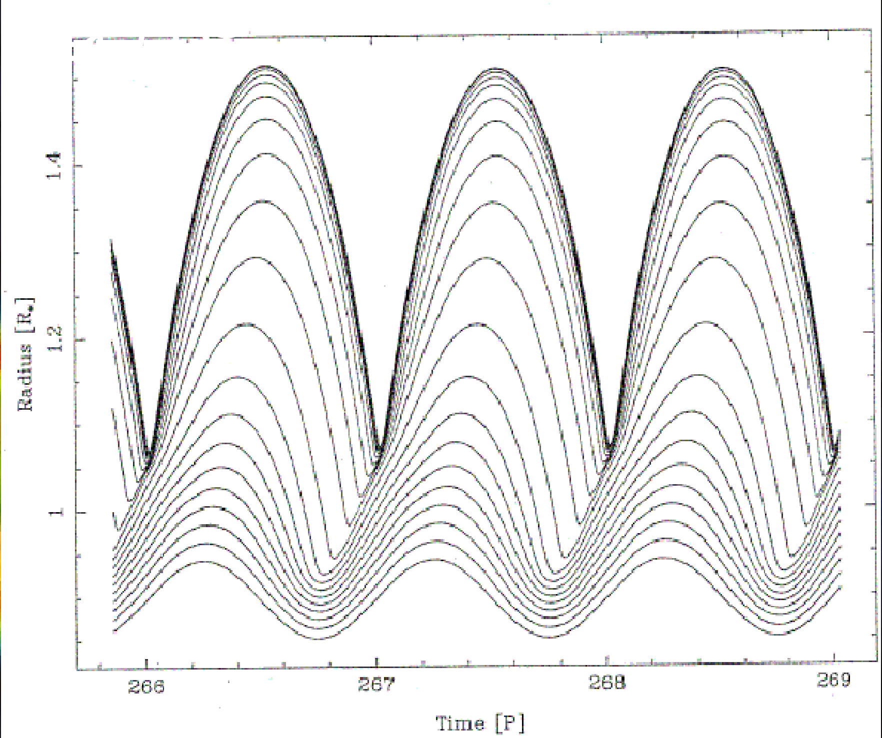
- Here the pulsating atmosphere comes to the rescue: the pulsational movements periodically 'lift up' the atmosphere.
- How much:

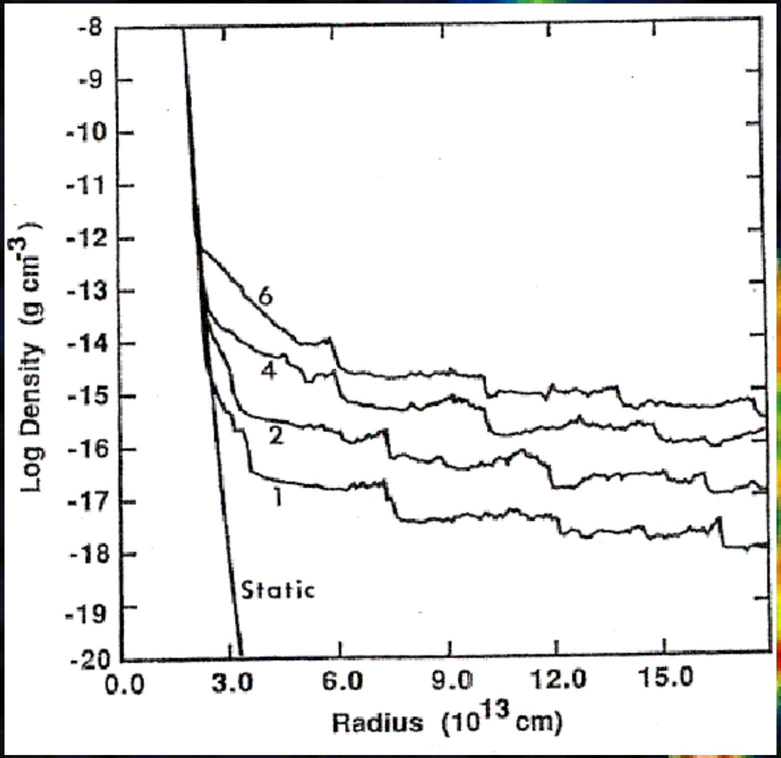
$$\frac{1}{2} M_{\mathrm{s}} v_0^2 = -GMM_{\mathrm{s}} \left(\frac{1}{r_{\mathrm{max}}} - \frac{1}{r_0} \right) \qquad \Rightarrow$$

$$\frac{r_{\mathrm{max}}}{r_0} = \left(1 - \left(\frac{v_0}{v_{\mathrm{esc}}} \right)^2 \right)^{-1}$$

- $M=1\ M_\odot$, $R_*=300\ R_\odot$ $\rightarrow$ $v_{esc}=35$ km/s.
- With $v_0=10$ km/s, we get $r=1.3R_*$

Detailed Pulsation Calculations





$r=1.5R_*$

Atmospheric density profile changed!

Radiation Pressure Force

- The force responsible for mass loss from AGB stars is radiation pressure on dust.
- For this force we can write $$\Gamma_{\rm d} = \frac{\kappa_{\rm rp} L_*}{4\pi c G M}$$
- What is the maximum we can get out of the radiation field?
- The radiation carries a momentum hv/c per photon, or a total momentum rate of L/c. Equating this to the total momentum rate in the wind, we get
$$\dot{M} = L_* / (c v_\infty)\,,$$
- This called the *single scattering limit* since it assumes that each photon only interacts once with a dust particle.

Multiple Scattering

- However, at the radiation energy rate (L) and compare this to the kinetic energy rate in the wind:

$$L_{\mathrm{wind}} = \frac{1}{2}\dot{M}v_\infty^2 \quad \Rightarrow \quad L_{\mathrm{wind}}/L_* = \frac{1}{2}v_\infty/c \ll 1$$

- More can be extracted through *multiple scattering*!

$$\mathrm{d}m = 4\pi r^2 \mathrm{d}r$$

$$v\frac{\mathrm{d}v}{\mathrm{d}r} = -\frac{1}{\rho}\frac{\mathrm{d}p}{\mathrm{d}r} - \frac{GM}{r^2} + f(r)$$

$$\dot{M}v_\infty + \sim 0 + \sim 0 + \int_{r_\mathrm{c}}^{\infty} \frac{GM}{r^2}(1-\Gamma_\mathrm{d})\rho 4\pi r^2 \mathrm{d}r = 0$$

$$\tau_\mathrm{w} = \int_{r_\mathrm{c}}^{\infty} \kappa_{\mathrm{rp}}\rho \mathrm{d}r \quad \Rightarrow \quad \dot{M}v_\infty = \frac{L_*}{c}\left(\frac{\Gamma_\mathrm{d}-1}{\Gamma_\mathrm{d}}\right)\tau_\mathrm{w} \approx \frac{L_*}{c}\tau_\mathrm{w} \quad \text{for} \quad \Gamma_\mathrm{d} \gg 1$$

Multiple Scattering Limit

$$\dot{M} v_\infty = \frac{L_*}{c}\left(\frac{\Gamma_\mathrm{d}-1}{\Gamma_\mathrm{d}}\right)\tau_\mathrm{w} \approx \frac{L_*}{c}\tau_\mathrm{w} \quad \text{for} \quad \Gamma_\mathrm{d} \gg 1$$

- Absolute energy limit: $$\tau_\mathrm{w} < \frac{2c}{v_\infty}$$
- More realistic: $$\tau_\mathrm{w} < \frac{c}{v_\infty} = 27\sqrt{\frac{\dot{M}/10^{-5}}{L/10^5}}$$
- So, through multiple scattering, the wind momentum can be an order of magnitude higher!

Wind Velocity

- The final wind velocity can be obtained from looking at the wind equation beyond r_c:

$$v\frac{\mathrm{d}v}{\mathrm{d}r} = -\frac{1}{\rho}\frac{\mathrm{d}p}{\mathrm{d}r} - \frac{GM}{r^2} + f(r) \quad \xrightarrow{\mathrm{d}p/\mathrm{d}r \approx 0} \quad v\frac{\mathrm{d}v}{\mathrm{d}r} = \frac{1}{2}\frac{\mathrm{d}v^2}{\mathrm{d}r} = \frac{GM}{r^2}(\Gamma_\mathrm{d} - 1)$$

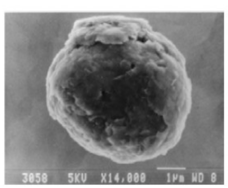
$$\Rightarrow \quad v^2(r) = v^2(r_\mathrm{c}) + v^2_\infty\left(1 - \frac{r_\mathrm{c}}{r}\right)$$

$$v^2_\infty \equiv \frac{2GM_*}{r_\mathrm{c}}(\Gamma_\mathrm{d} - 1) = v_\mathrm{esc}\frac{R_*}{r_\mathrm{c}}(\Gamma_\mathrm{d} - 1)$$

- $M = 1\ M_\odot$, $L = 10^4\ L_\odot$, $r_c = 2\times10^{14}$ cm $\rightarrow v_\infty = 16$ km/s.

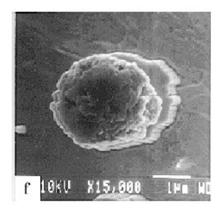
Dust Formation

- Radiation pressure on dust, so we need dust formation.
- Two types of dust
  - M-type stars: ’dirty’ silicates
  - C-type stars: amorphous carbon grains
- Dust formation:
  - Hydrodynamics: density, temperature
  - Chemistry: first step is molecules
  - Nucleation: condensing seed nuclei from gas phase
  - Solid-gas interaction: grain growth

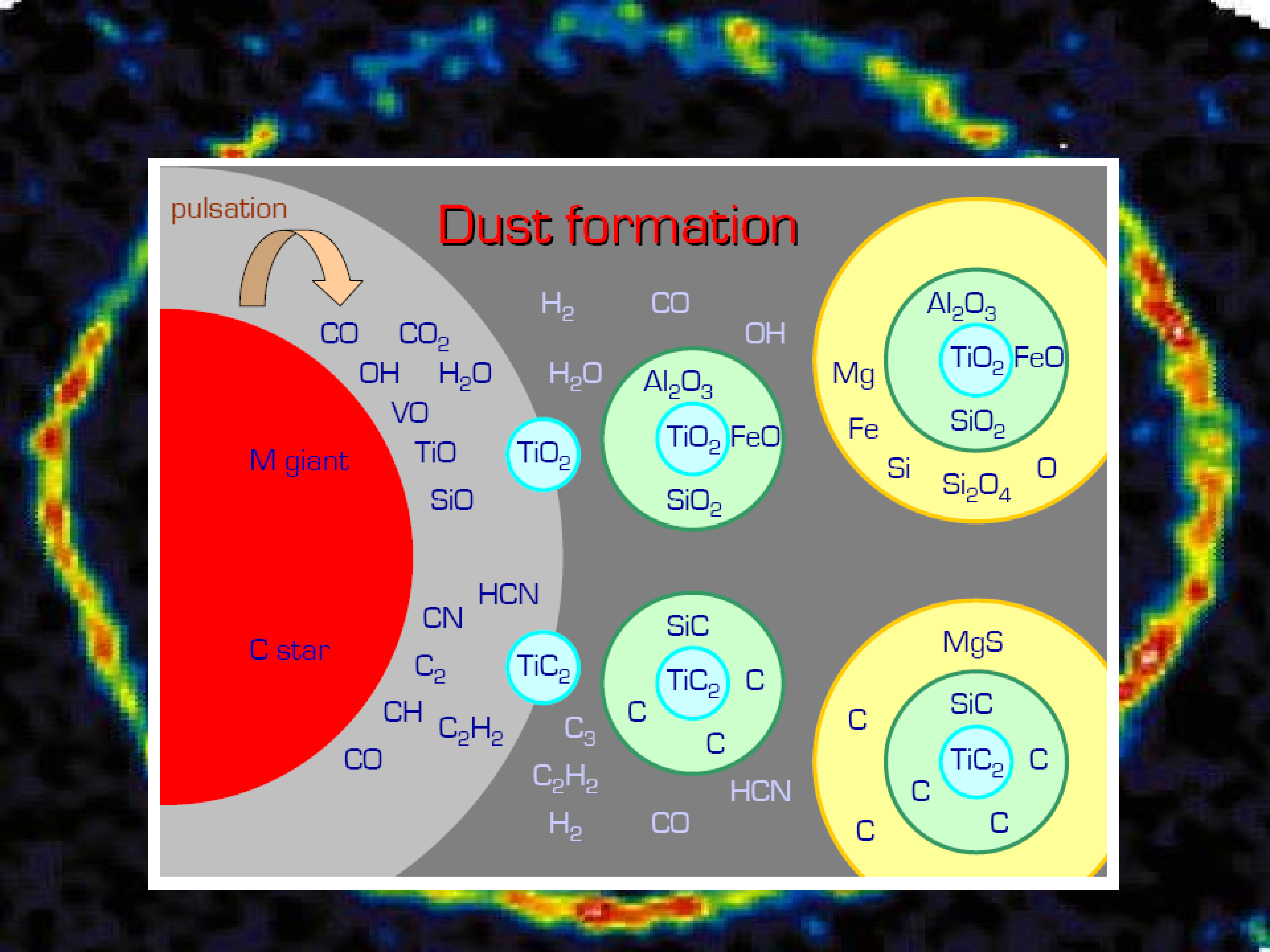


Graphite
2 parts per million
Size ~1-10μm

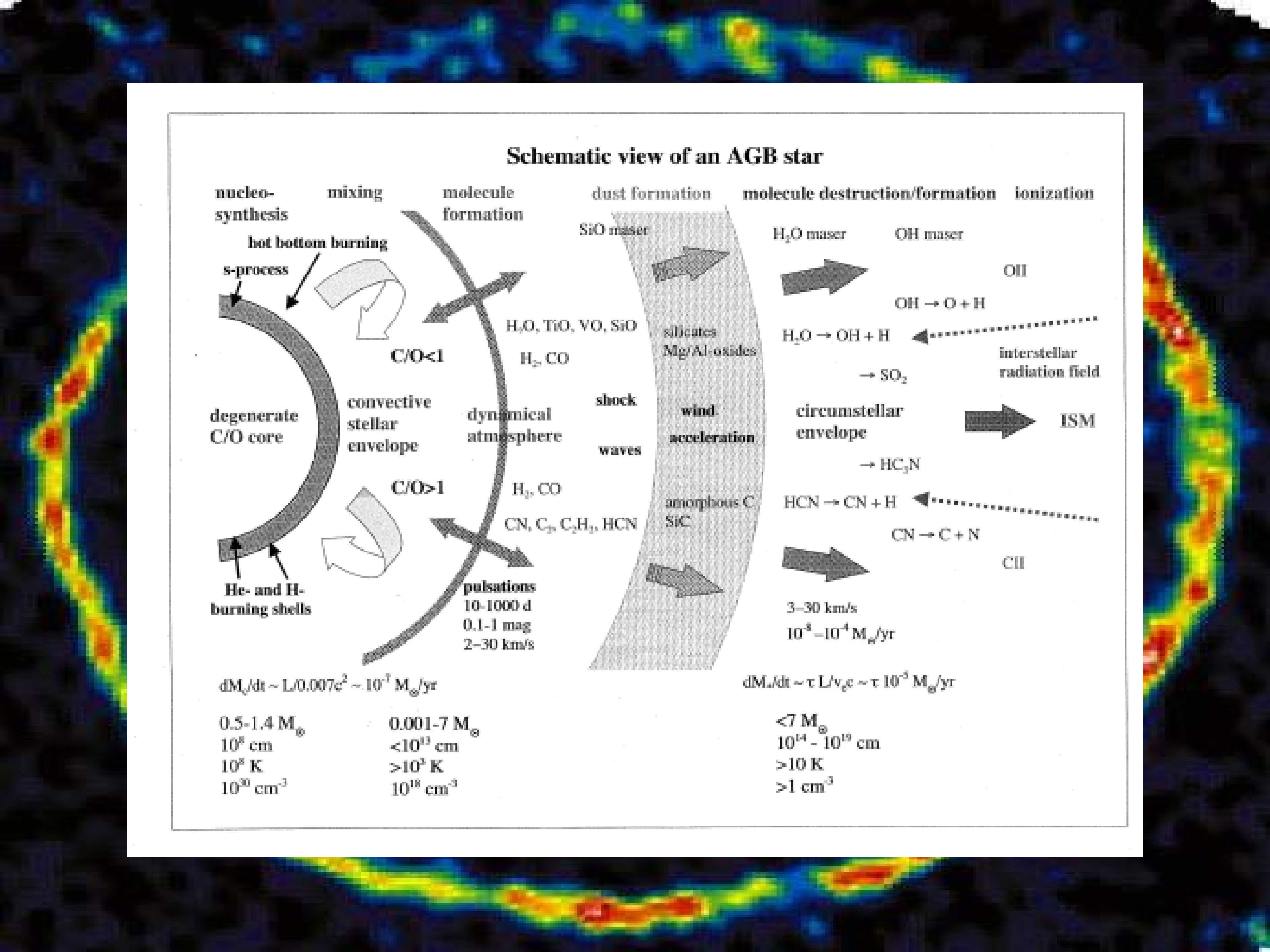
Presolar grains extracted from meteorites



Al_2O_3
0.1 parts per million
Size ~ 1-5μm



Dust formation
pulsation
M giant
C star
CO
CO$_2$
OH
H$_2$O
VO
TiO
SiO
H$_2$
CO
OH
H$_2$O
TiO$_2$
Al$_2$O$_3$
TiO$_2$
FeO
SiO$_2$
Al$_2$O$_3$
TiO$_2$
FeO
SiO$_2$
Mg
Fe
Si
Si$_2$O$_4$
O
HCN
CN
C$_2$
CH
C$_2$H$_2$
CO
TiC$_2$
C$_3$
C$_2$H$_2$
H$_2$
CO
HCN
SiC
TiC$_2$
C
C
C
MgS
SiC
TiC$_2$
C
C
C
C
C


Schematic view of an AGB star
nucleo-synthesis
mixing
molecule formation
dust formation
molecule destruction/formation
ionization
hot bottom burning
s-process
SiO maser
H2O maser
OH maser
OII
OH → O + H
H2O, TiO, VO, SiO
silicates Mg/Al-oxides
H2O → OH + H
interstellar radiation field
C/O<1
H2, CO
→ SO2
degenerate C/O core
convective stellar envelope
dynamical atmosphere
shock waves
wind acceleration
circumstellar envelope
ISM
→ HC3N
C/O>1
H2, CO
amorphous C SiC
HCN → CN + H
CN, C2, C2H2, HCN
CN → C + N
CII
He- and H-burning shells
pulsations
10-1000 d
0.1-1 mag
2–30 km/s
3–30 km/s
10^-8 –10^-4 M⊙/yr
dMc/dt ~ L/0.007c^2 ~ 10^-7 M⊙/yr
dMd/dt ~ τ L/ve c ~ τ 10^-5 M⊙/yr
0.5-1.4 M⊙
10^8 cm
10^8 K
10^30 cm^-3
0.001-7 M⊙
<10^13 cm
>10^3 K
10^18 cm^-3
<7 M⊙
10^14 - 10^19 cm
>10 K
>1 cm^-3

Dust Formation: Non-Equilibrium

- Temperature acts as a threshold
  - Set by dynamics and radiative transfer.
  - Generally decreases outward, but highly time dependent.
- Density determines efficiency
  - Set by dynamics.
- Dynamics (pulsations) sets the time scale
  - Shocks restrict time available, but also help by increasing the density.

- For dust to drive the mass loss, it needs to form in sufficient quantities at the right location ($r \sim r_c$)!

Complexity of Mass Loss Modelling

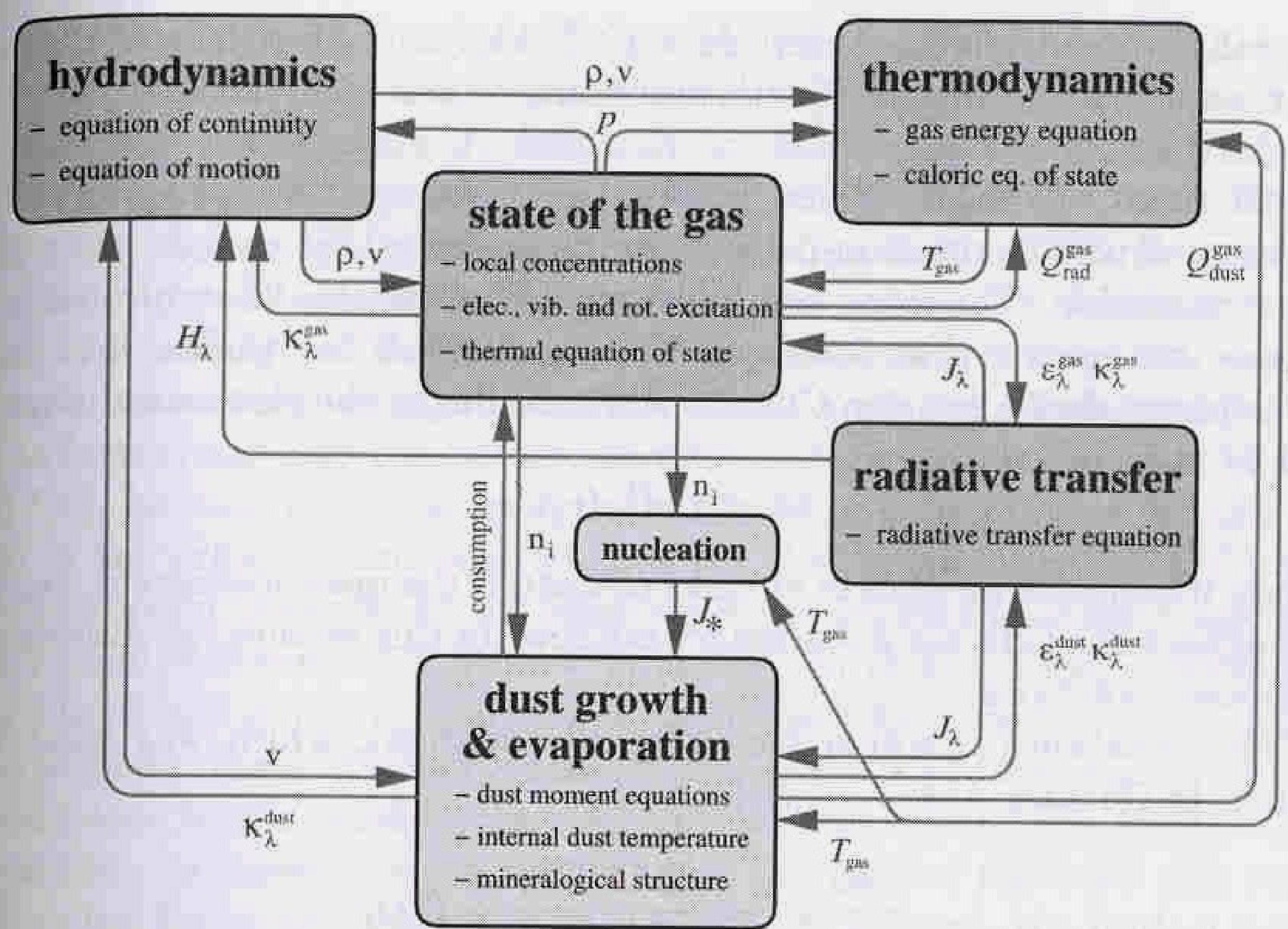
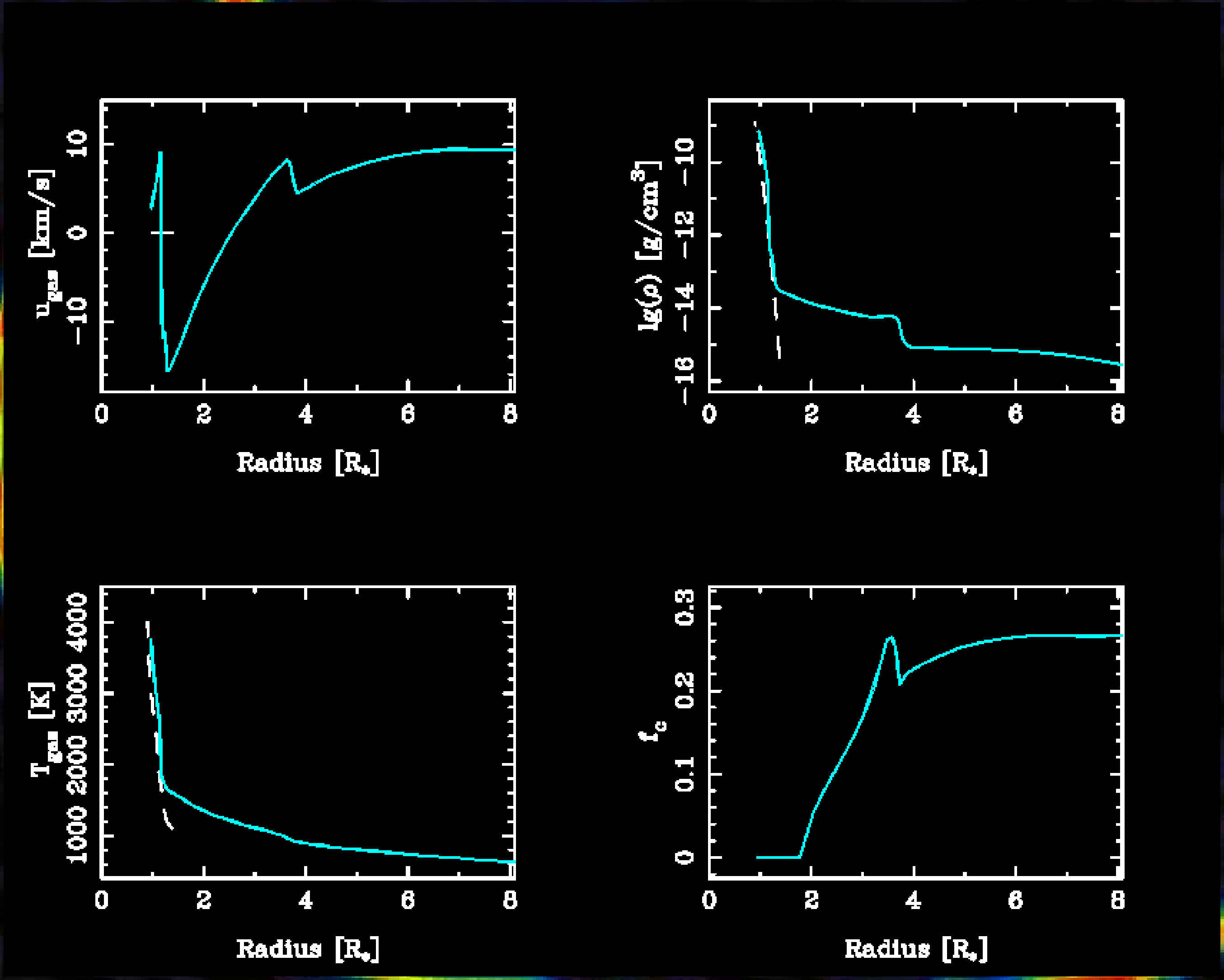


Fig. 6.2. Schematic overview of the interactions between the physical and chemical processes in the dust-forming AGB CSE. From [76]

Radiation-Hydrodynamic Model



Susanne Höfner (Uppsala)

Classical Nucleation Theory

- Statistical theory which only considers the ’size’ of the seed nuclei.
- *f(N):* the fraction of nuclei that contain *N* monomers (e.g. C-atoms).
- $\partial f(N_i)/\partial t$ = growth($N<N_i$) – growth($N>N_i$) – diminishment($N<N_i$) + diminishment($N>N_i$)

- Growth: sticking, absorption.
- Dimishment: evaporation, ’sputtering’, dust-dust collisions

- Since N can be 10^{12}, what is often solved for are *moments* of *f(N),* e.g. total surface area:

$$K_2 = \sum_{N_l}^{\infty} f(N) N^{2/3}$$

Gas-Dust Coupling

- Radiation pressure accelerates the dust particles, which form only some 1% of the mass. To launch a wind, momentum has to be transferred to the gas.
- This transfer happens through the so-called *drag force.*
- For small dust grains:

$$f_{\rm drag} = \sigma_{\rm d} n_{\rm g} n_{\rm d} m_{\rm g} \left| v_{\rm coll} \right| v_{\rm drag}$$

with $\quad v_{\rm drag} \equiv \left| v_{\rm g} - v_{\rm d} \right|$

and $\quad v_{\rm coll} = v_{\rm thermal} \sqrt{\frac{64}{9\pi} + \left(\frac{v_{\rm drag}}{v_{\rm thermal}} \right)^2}$

- The drag force tries to minimalize v_{drag}, but is also proportional to it → equilibrium value for v_{drag}.
- Often assumed $v_{drag} \approx 0$ (perfect coupling), but dependence of f_{drag} on grain size can give interesting (time-dependent) effects.

Dust around O-rich AGB Stars

- Models work well for C-stars.
- For O-stars, the seed nuclei are thought to be Al_2O_3 (corundum), Fe, Ti-oxides.
- Difficult to condense these out at the right position.
- 'Dirty' silicates (Mg_xSiO_4, Fe_xSiO_4) needed for high opacity.
- No current working model.

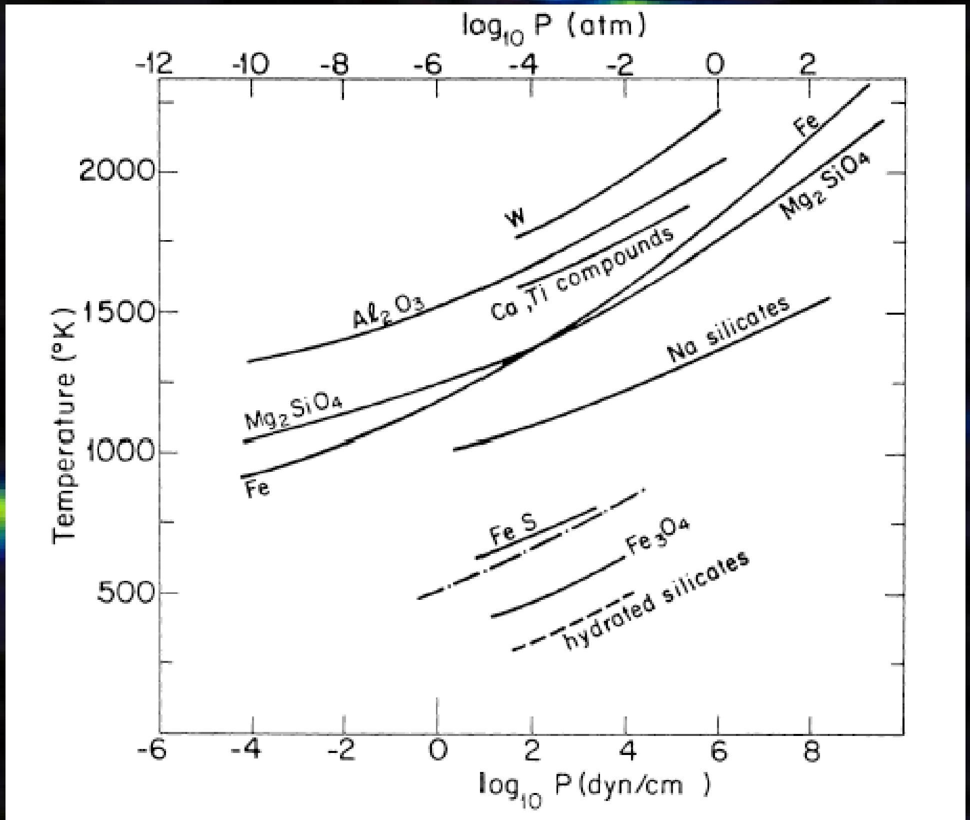


Figure 2 Plots of condensation temperature versus total gas pressure P for various minerals, assuming normal cosmic abundances. The dash-dot curve indicates conditions where half of the CO is destroyed by interaction with H_2.