Physical Processes involving Dust in Protoplanetary Disks

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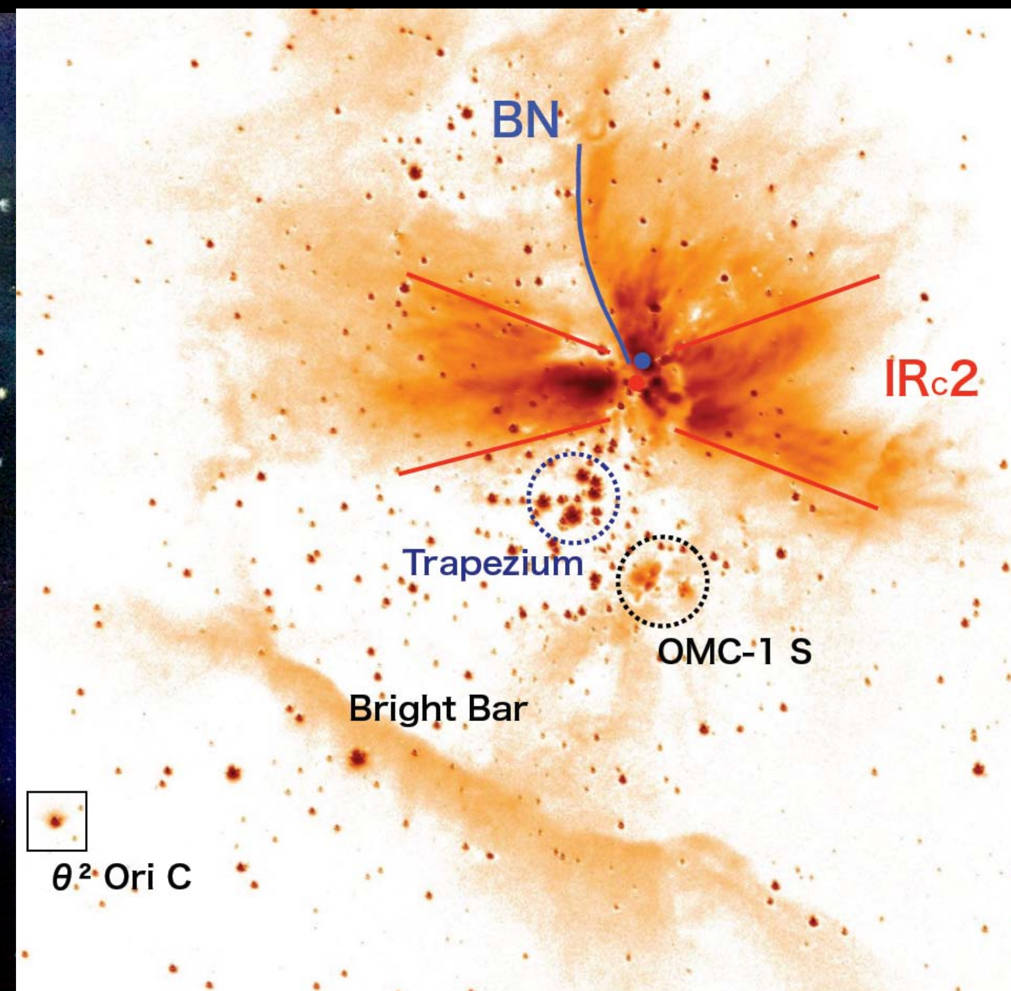
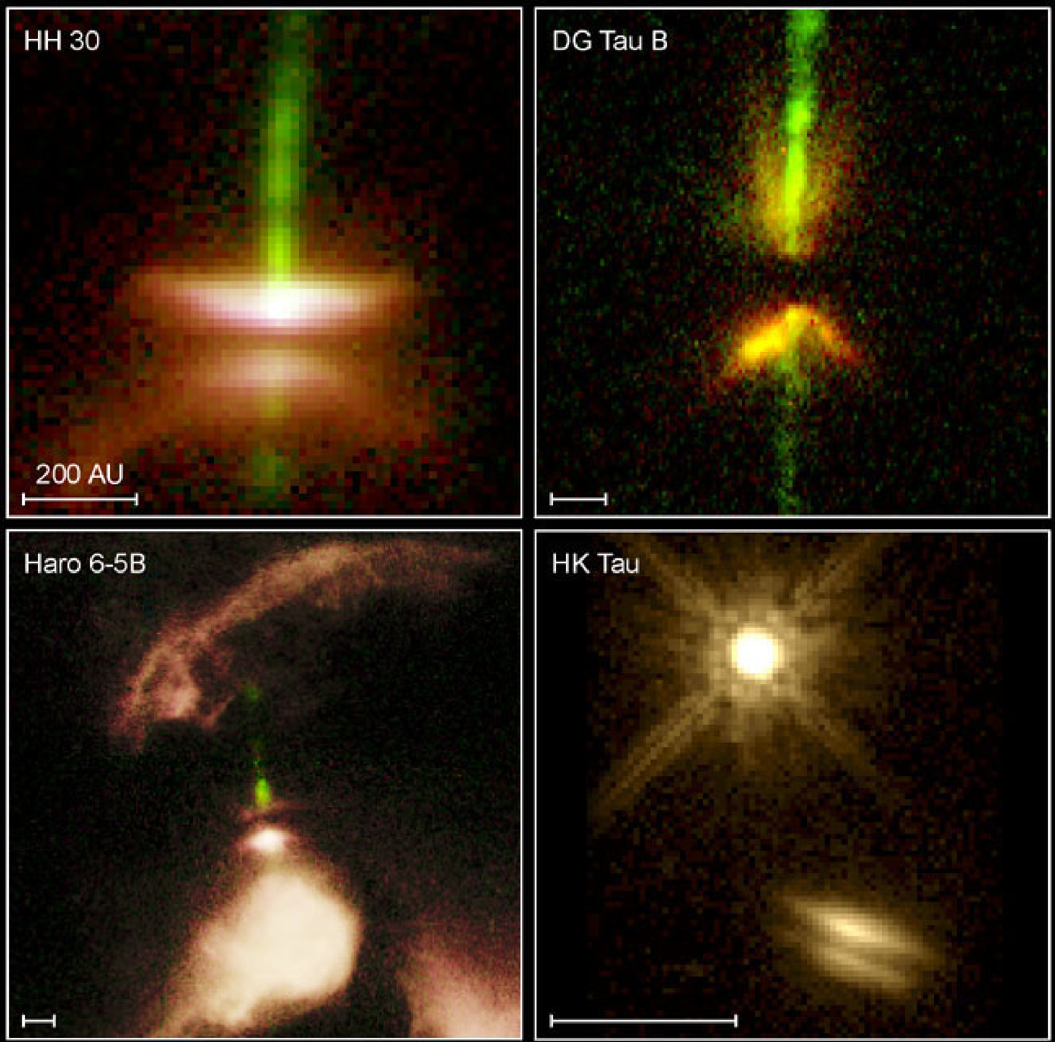
Birth place of stars and planetary systems: Molecular clouds



Orion nebula as viewed through IR polalization

Tamura et al. 2006

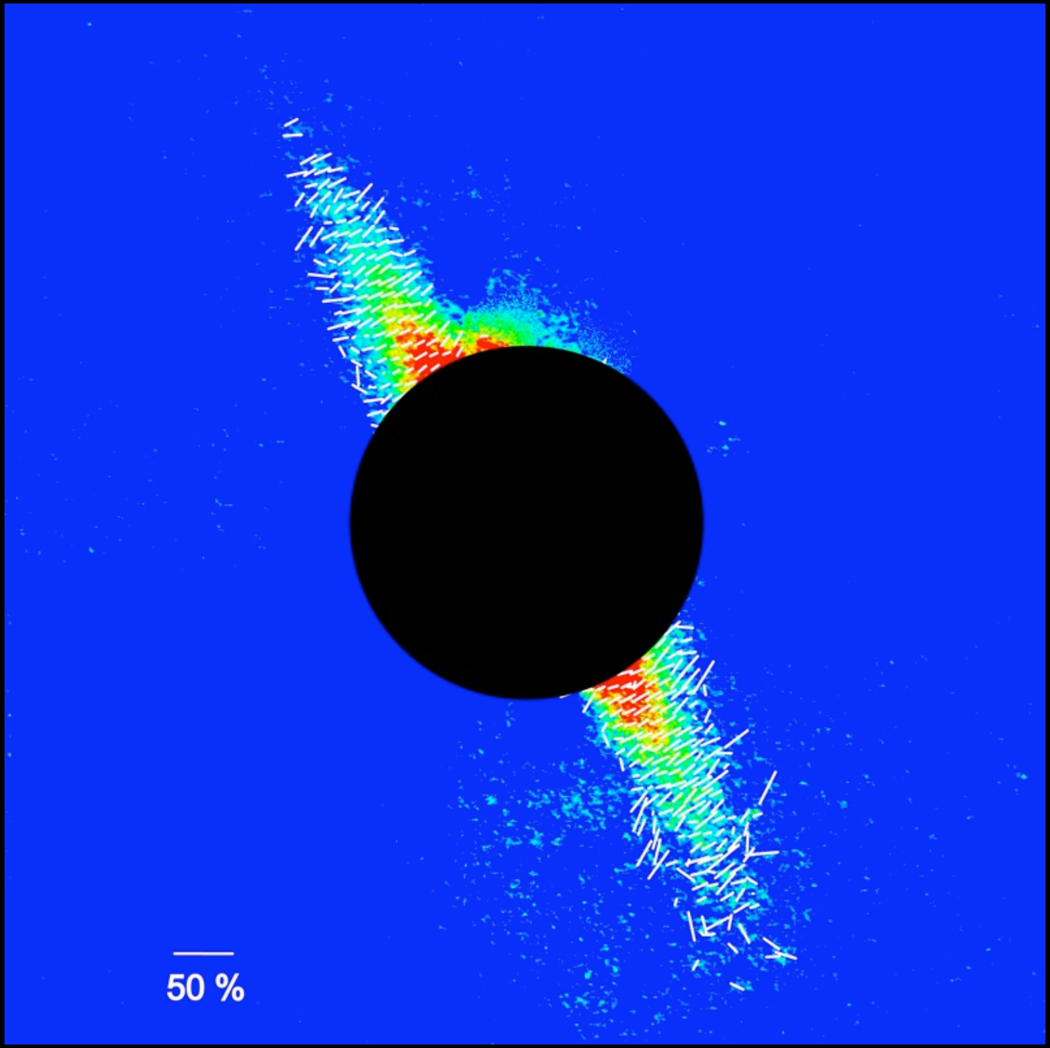
Protoplanetary disks
Disks around YSOs: Birth place of planets



Disks around Young Stars **HST • WFPC2**
PRC99-05b • STScI OPO
C. Burrows and J. Krist (STScI), K. Stapelfeldt (JPL) and NASA

Also Ito's talk

Debris disk of dust around a main-sequence star
Polarimetric observation of β Pic



Tamura et al. 2006
(collaboration with NAOJ, Nagoya & Sapporo groups)

Standard model

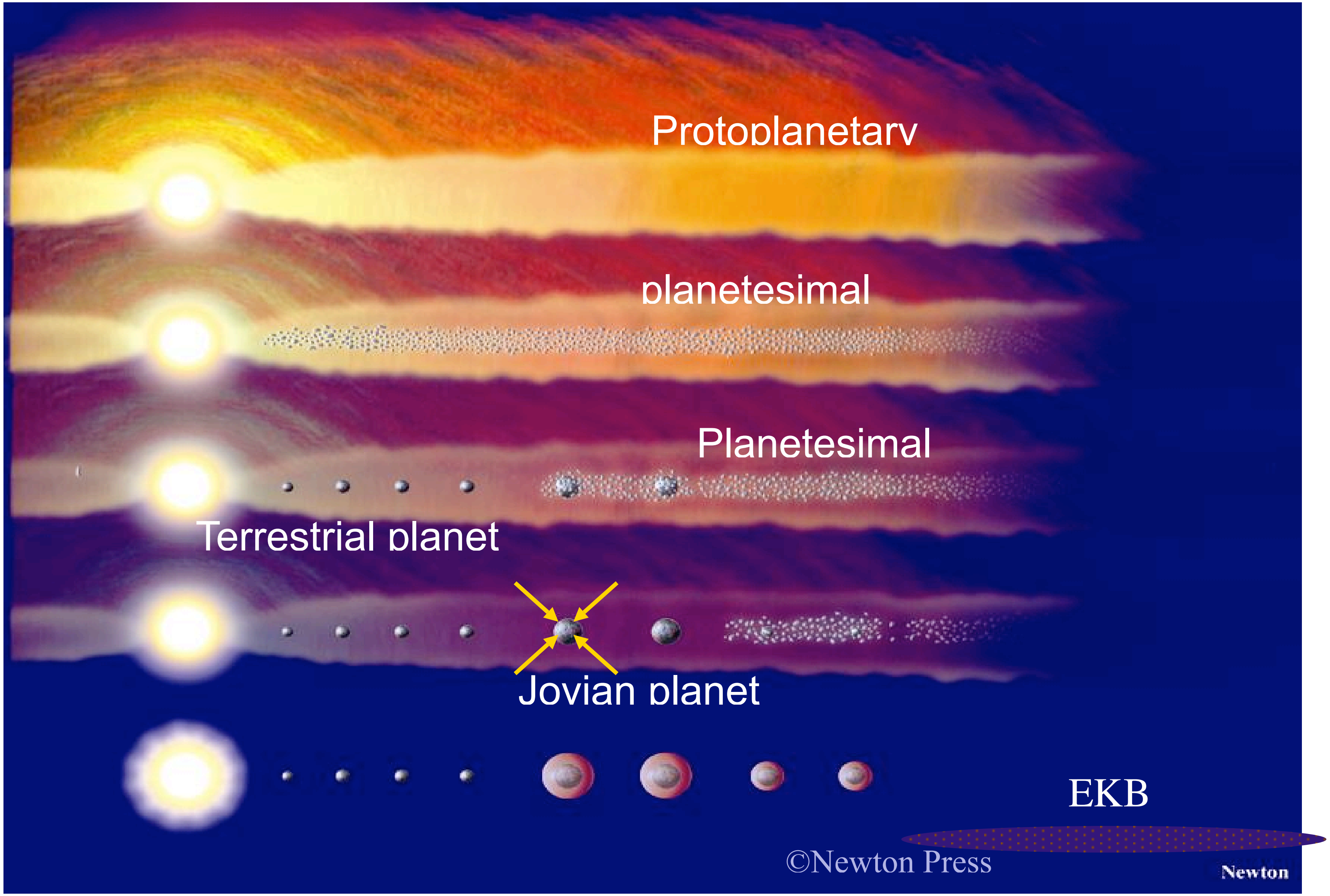
age

$10^{5\text{-}6}$yr

$10^{5\text{-}7}$yr

$10^{6\text{-}8}$yr

10^{9}yr



(Also Takeuchi's talk)

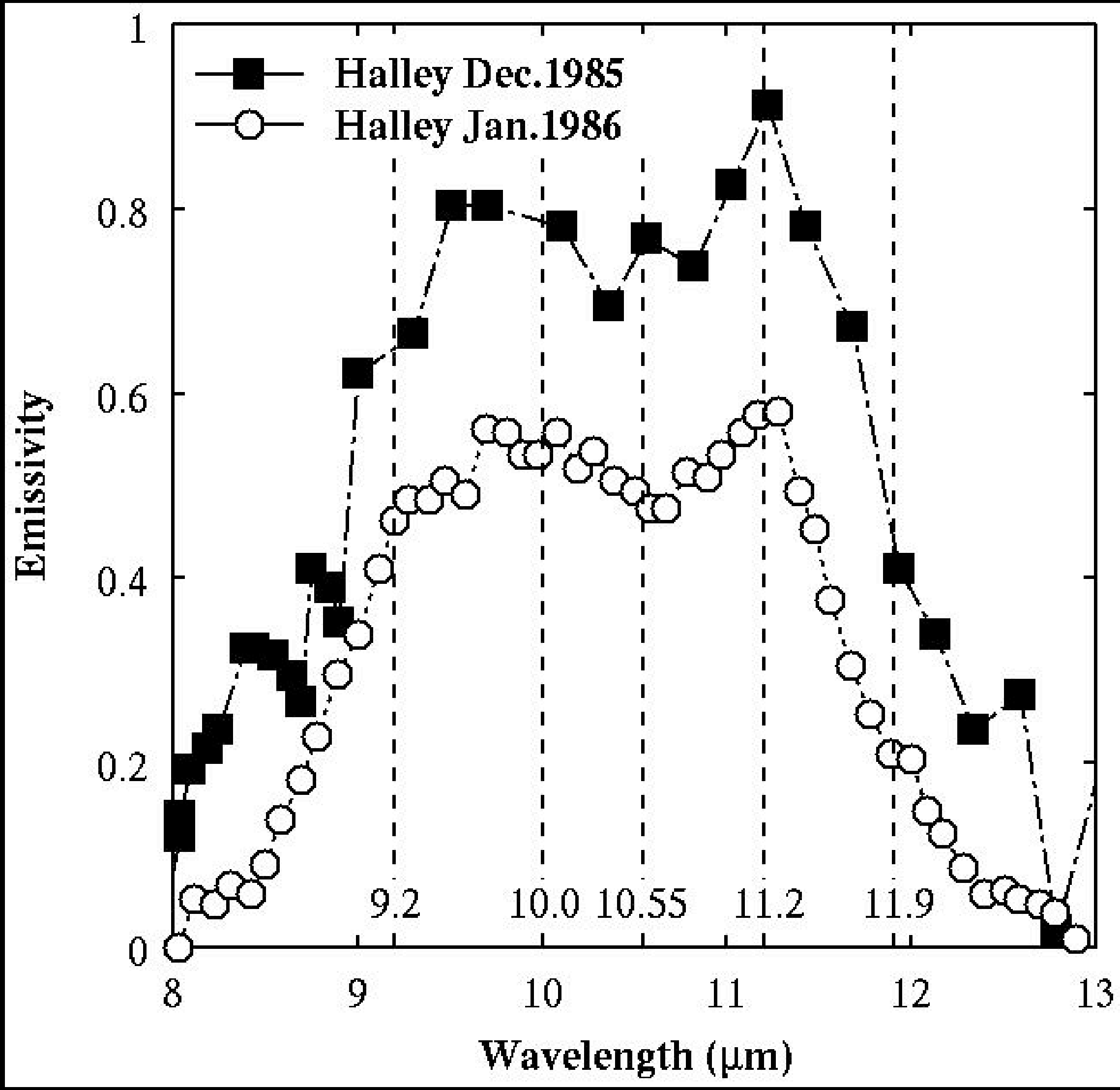
Elementary processes involving dust in protoplanetray disks (in collaborations with Kobe, Tohoku, Kyoto, Nagoya, NAOJ, Jena, & Helsinki groups)

- Growth & destruction of dust aggtegates
  - Tanakaka, Wada, Suyama (2007, 2008, 2009)
  - Arakawa (experiment of dust collisions)
- Crystallization of silicate dust
- Optics of dust aggregates including transfer of polarized light by scattering
  - Kimura et al. 2008, 2009, Zubko 2009, Fukue et al. in progress
- Dust dynamics in debris disks (Jian Ing-Guey's talk)
  - Kobayashi et al. 2008, 2009 (numerical & analytic models)
  - Minato et al. 2004, 2006 (stellar wind drag)

Low-temperature crystallization of dust in space

in collaboration with
K.K. Tanaka
(ILTS, Hokkaido University)
H. Kimura
(CPS, Kobe University)

First detection of crystalline silicate



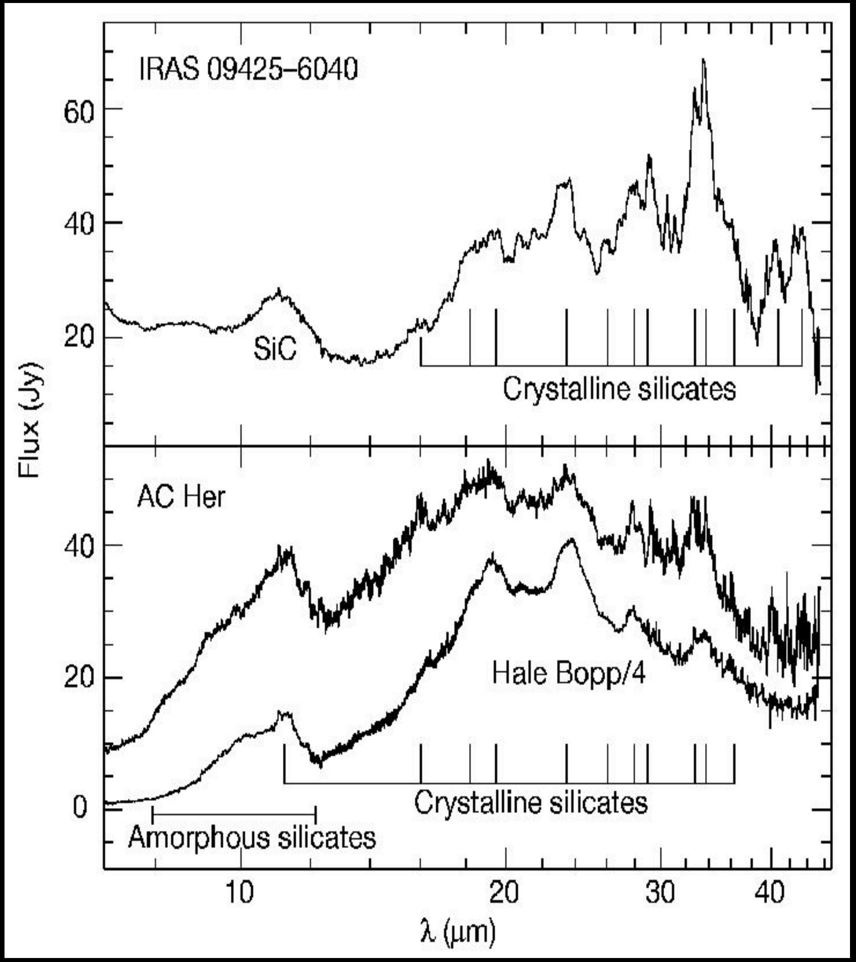
(Campins and Ryan 1989, Bregman et al. 1987)

Similar features have been observed in several comets.

Crystalline silicate in various kinds of objects

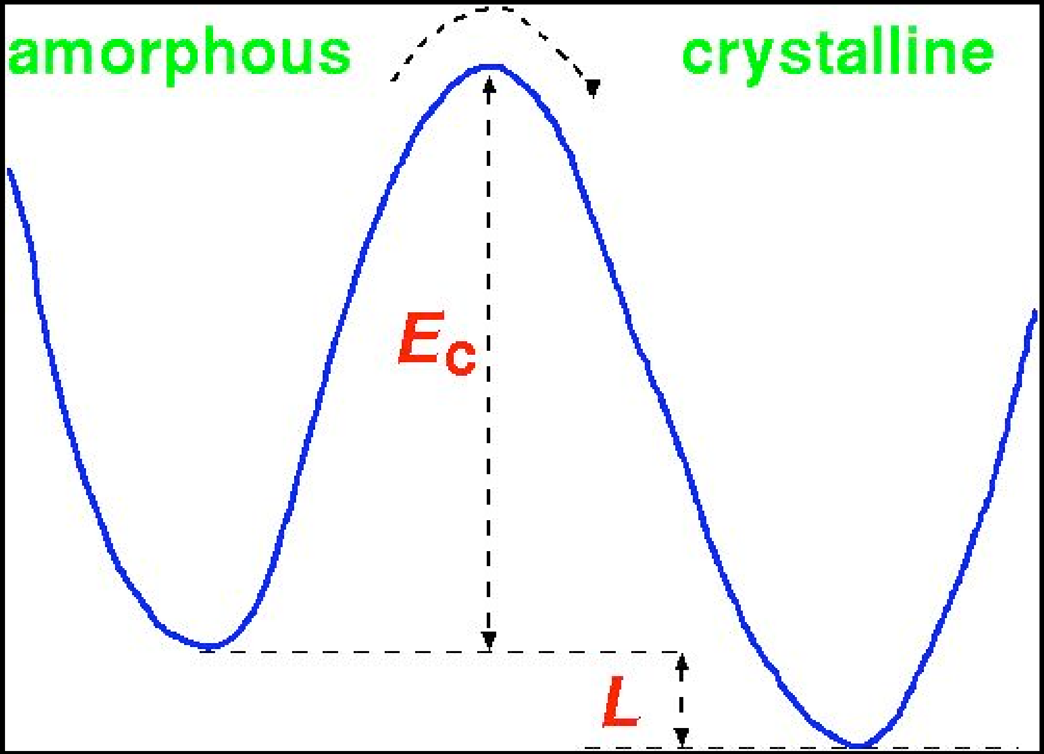
(Hanner 1999, 2003)

- Observed in
  - evolved stars
    - C-rich giant stars, post AGB stars
  - Herbig Ae/Be stars
  - T Tauri stars
  - young MS stars
  - Comets
  - ZL dust
  - IDPs
  - other galaxies (ULIRG)
- Not observed in
  - ISM & molecular clouds
  - Protostars



(Molster et al. 1999)

Crystallization: Transition from amorphous to crystalline state



internal energy : E(crystal) < E(amorphous)

- L : latent heat of crystallization
- must overcome energy barrier Ec for crystallization

Energy source to overcome Ec

Annealing induced by fluctuation of thermal energy

(Hallenbeck et al. 1998, Fabian et al. 2000, Kamitsuji et al. 2005, and many others)

In protoplanetary diks, crystalline materials are transported from hot inner region to outer colid regions by:

- radilal diffusion, bipolar flows (Shu et al. 1997, Gail 2001)
- turbulent diffusion (Gail 2001, Keller & Gail 2004)

The fraction of crystalline silicate required to explain cometary spectra can be realized.
But
need fine-tuning of the parameters such as gas viscosiity

Correlation of
crystalline mass fraction
with
disk properties
such as stellar luminosities and accretion rate?

But

Observations of a large sample of protoplantary disks in Taurus-Auguriga cluster using Spitzer Space Telescope (Watson et al. 2009, ApJ, 180, 84)
show

No Correlation !

Energy source to overcome Ec

Annealing induced by fluctuation of thermal energy

(Hallenbeck et al. 1998, Fabian et al. 2000, Kamitsuji et al. 2005, and many others)

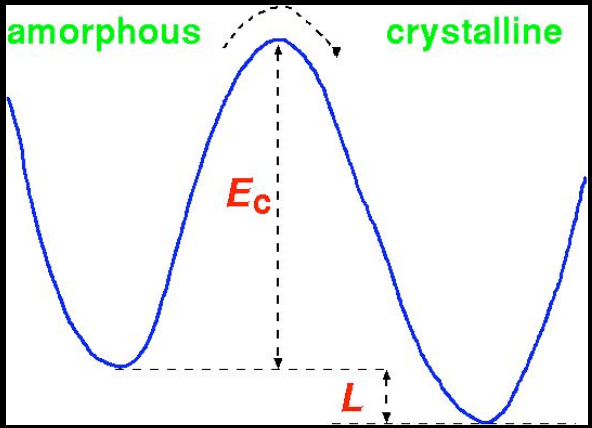
But other energy sources:

- irradiation of electrons or high energy particles

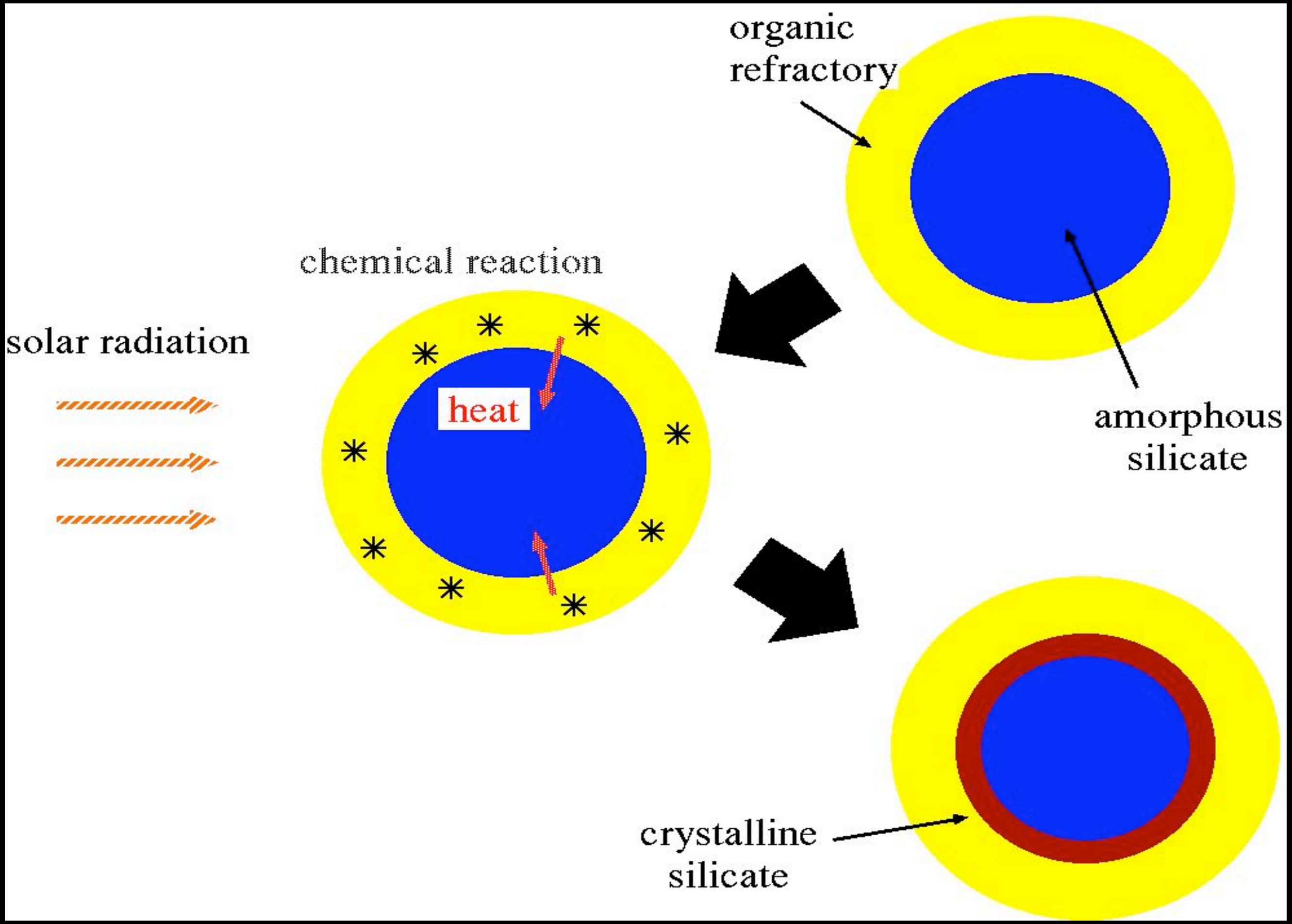
  (Carrez et al. 2002, Y. Kimura et al. 2008)

- heat of chemical reactions

  (Yamamoto & Chigai 2005, Yamamoto et al. 2009)



Basic idea of crystallization by heat of reactions



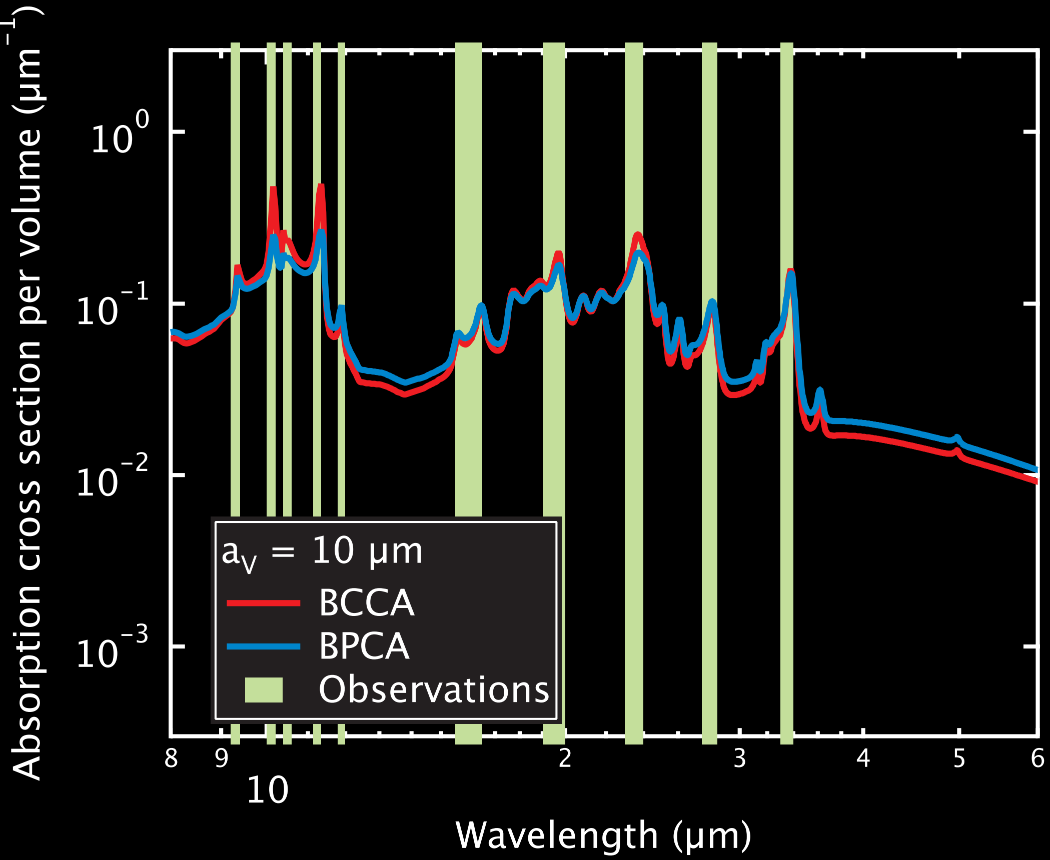
0) Suppose a silicate grain coated with a mantle including chemically reactive molecules (radicals).

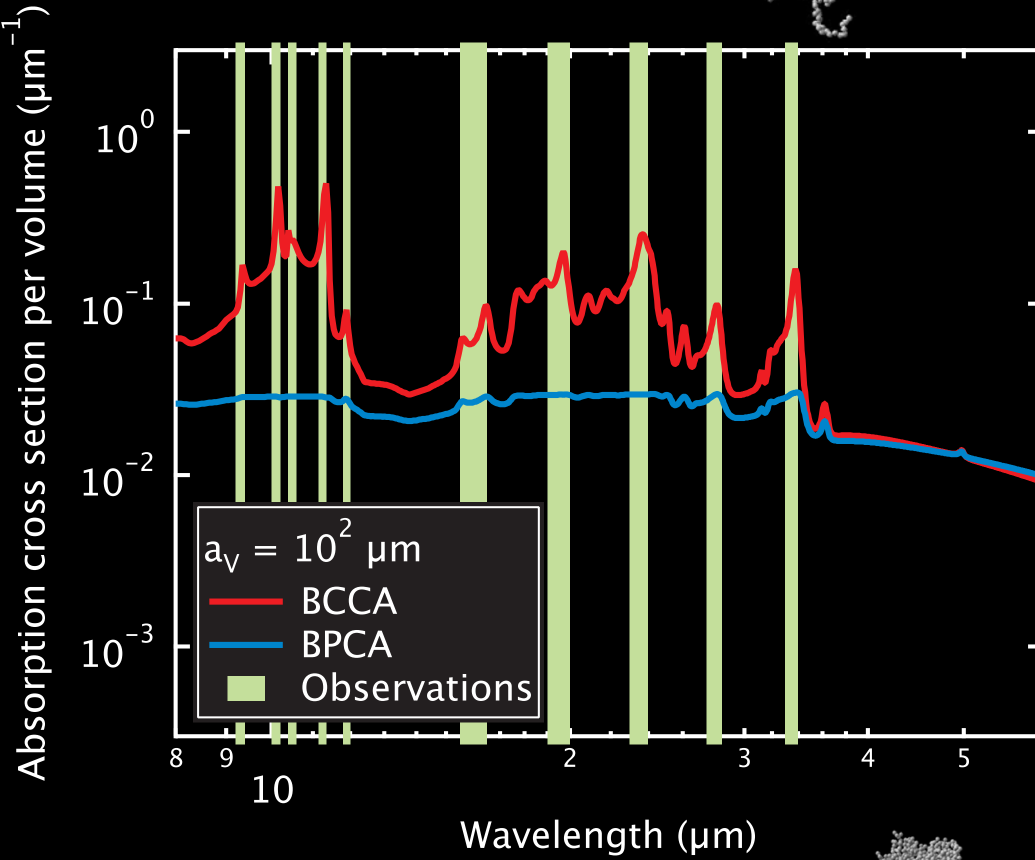
1) Moderate heating induces chemical reactions in the mantle

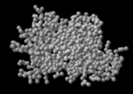
2) heat of reactions leads to crystallization

Some simplifications

Dependence of Infrared Features on the Shape of Dust Aggregates (Kimura et al. 2009)







Disappearance of the silicate feature does not necessarily imply dust growth but compaction.

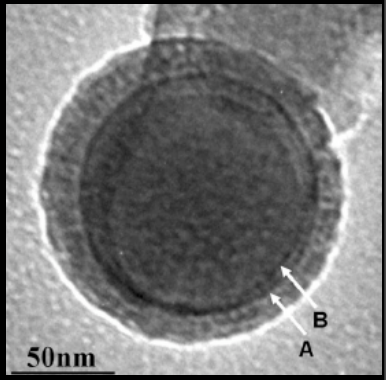
This was just a theoretical speculation.

We needed experimental verification.

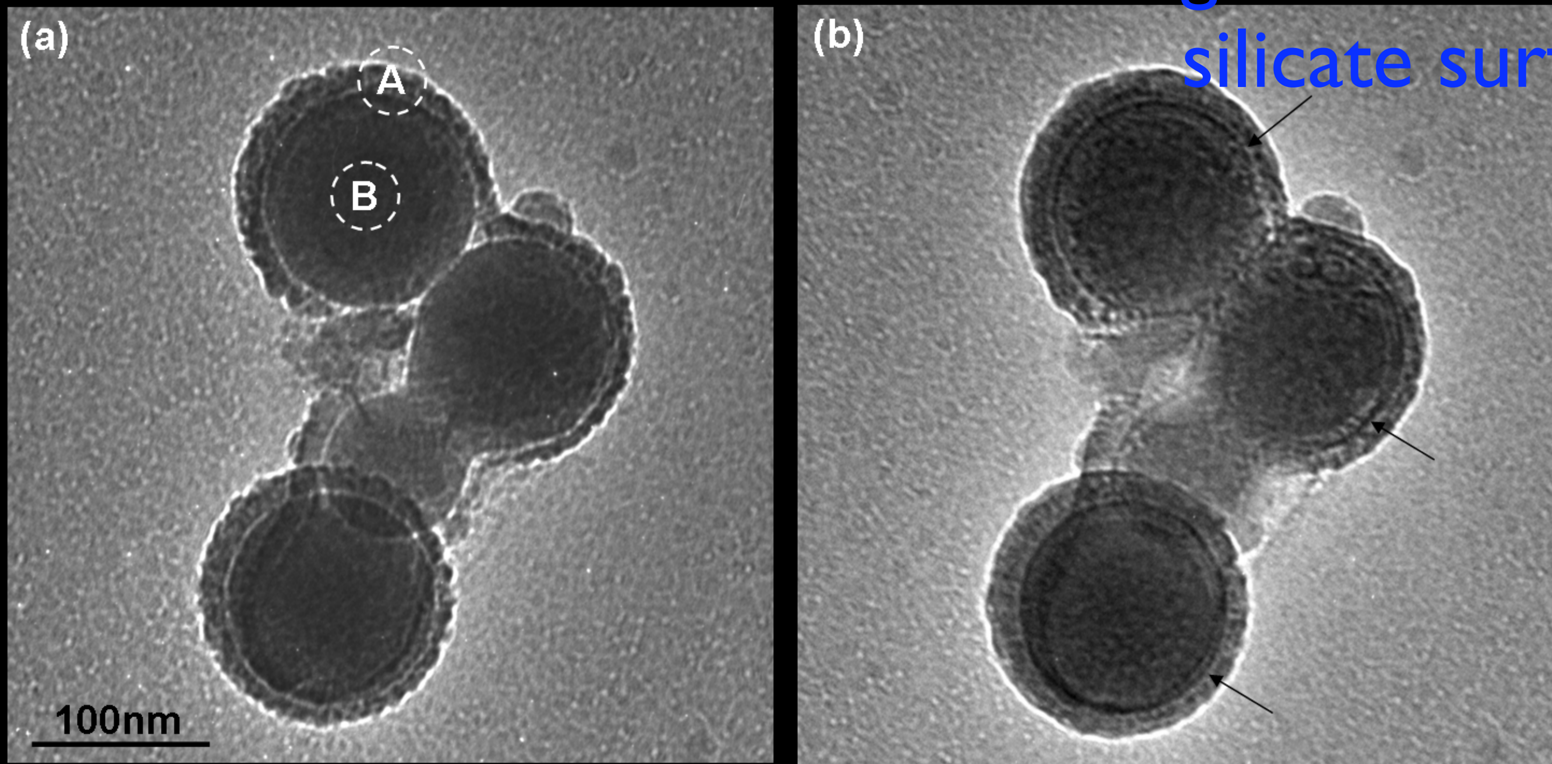
A series of experiments by Kaito's group

1. amorphous Mg_2SiO_4 particles
   - Tc = 800 C (Kamitsuji et al. 2005)
2. amorphous Mg_2SiO_4 particles covered with amorphous carbon
   - Tc = 600 C (Kaito et al. 2007a)

3. Experiment by Kaito et al. (2007b, ApJ, 666, L157)



- sample:
  - amophous particles of Mg_2SiO_4 composition covered with amorphous carbon produced in CH_4 gas atmosphere
  - a = 25 - 30 nm, h = 10 - 30 nm
- Crystallization at room temperature when the particles are exposed to air
  - thickness of crystallized region: 3 - 10 nm



30 min 4200 min

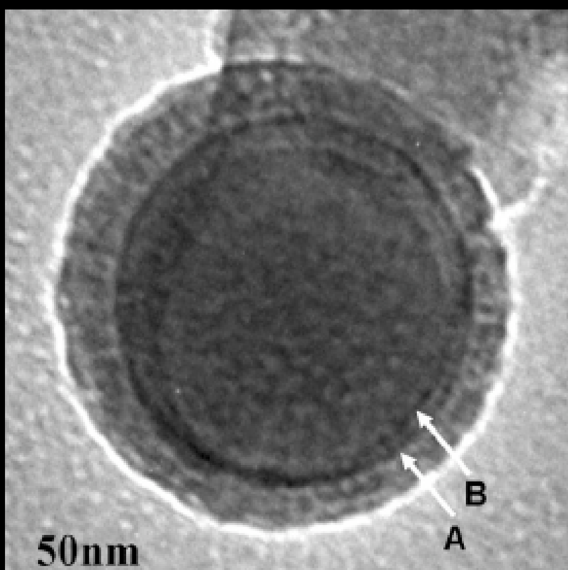
at room temperature

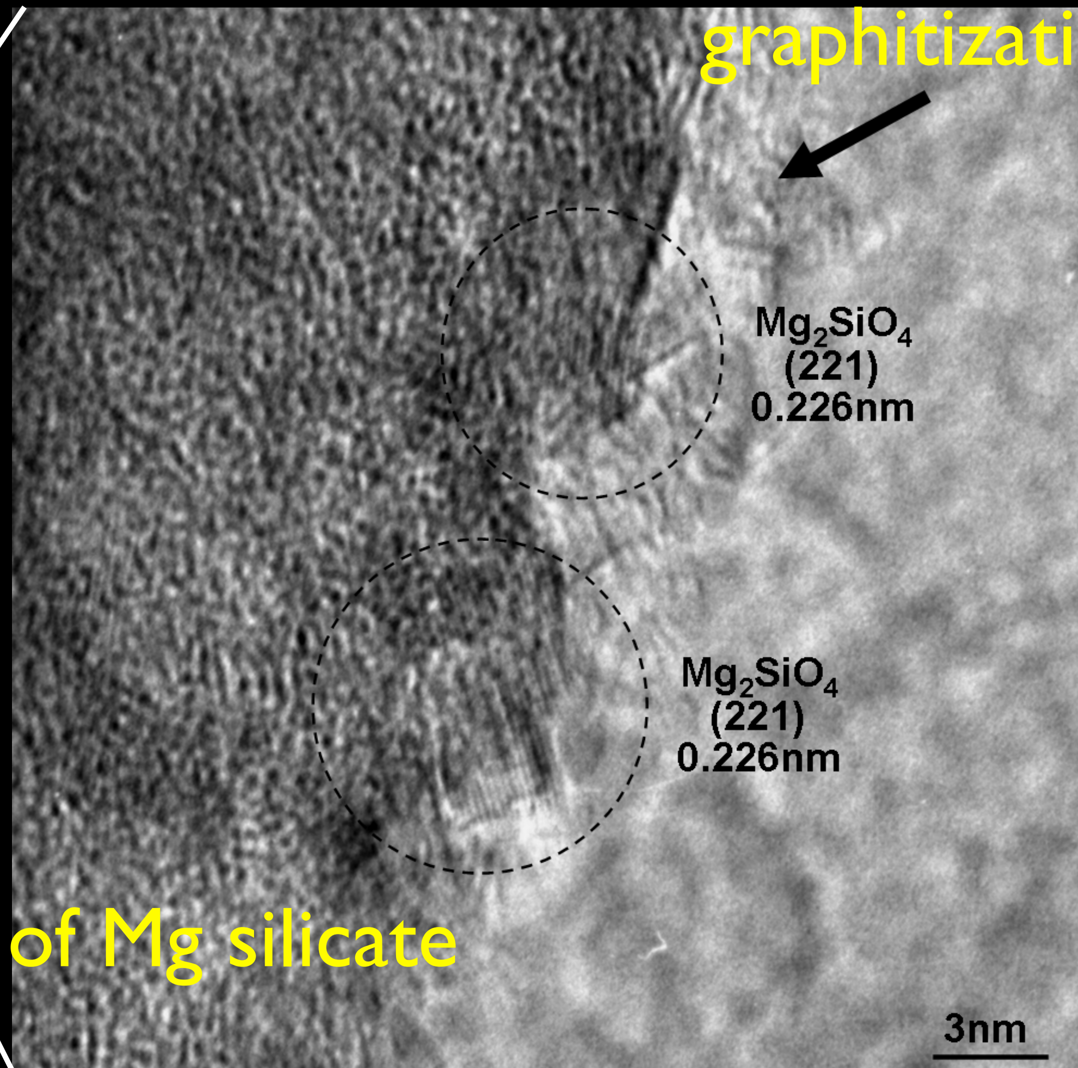
A: carbon layer produced by arc-discharge of carbon in CH_4 atmosphere (10^{-3} Torr)

B: Mg silicate grain

(Kaito et al. 2007b)

HREM image of a part of amorphous silicate



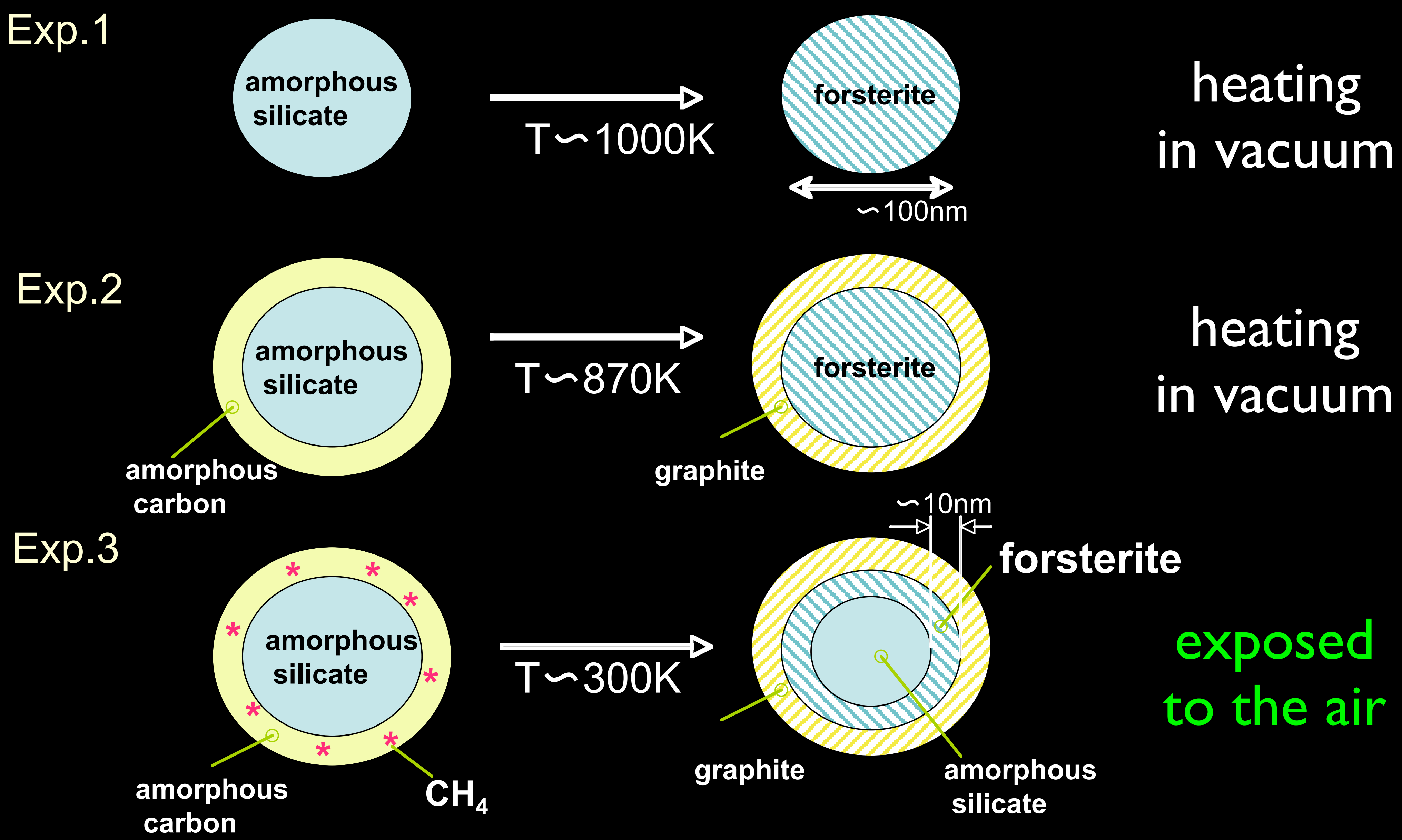


graphitization of C

crystallization of Mg silicate

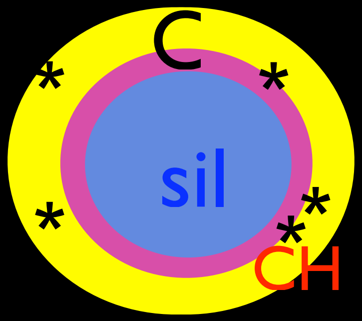
Kaito et al. 2007b

Series of experiments by Kaito et al. (Kamitsuji et al. 2005; Kaito et al. 2007a,b)

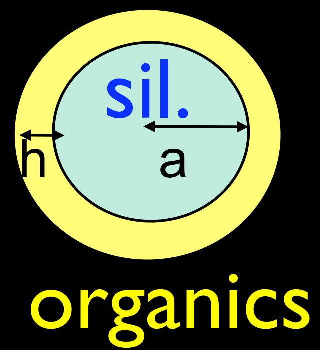


Picture of crystallization in Exp. 3 by Kaito et al. (2007b)

1. Release of heat of chemical reactions (oxidation of CH_4) in C mantle
2. Induce graphitization in the C mantle
3. Latent heat deposited by graphitization leads further temperature elevation
4. Induce crystallization of silicate from the interface of C mantle and silicate core
5. Cessation of crystallization due to cooling



Modelling of Exp. 3



Time variation of temperature of the particle

$$\frac{4}{3}\pi\rho c_{\rm p}\frac{dT}{dt} = \frac{4}{3}\pi[(a+h)^2 - a^3]\dot{\varepsilon} - \Lambda_{\rm air} - \Lambda_{\rm rad} + H_{\rm c} + H_{\rm sil}$$

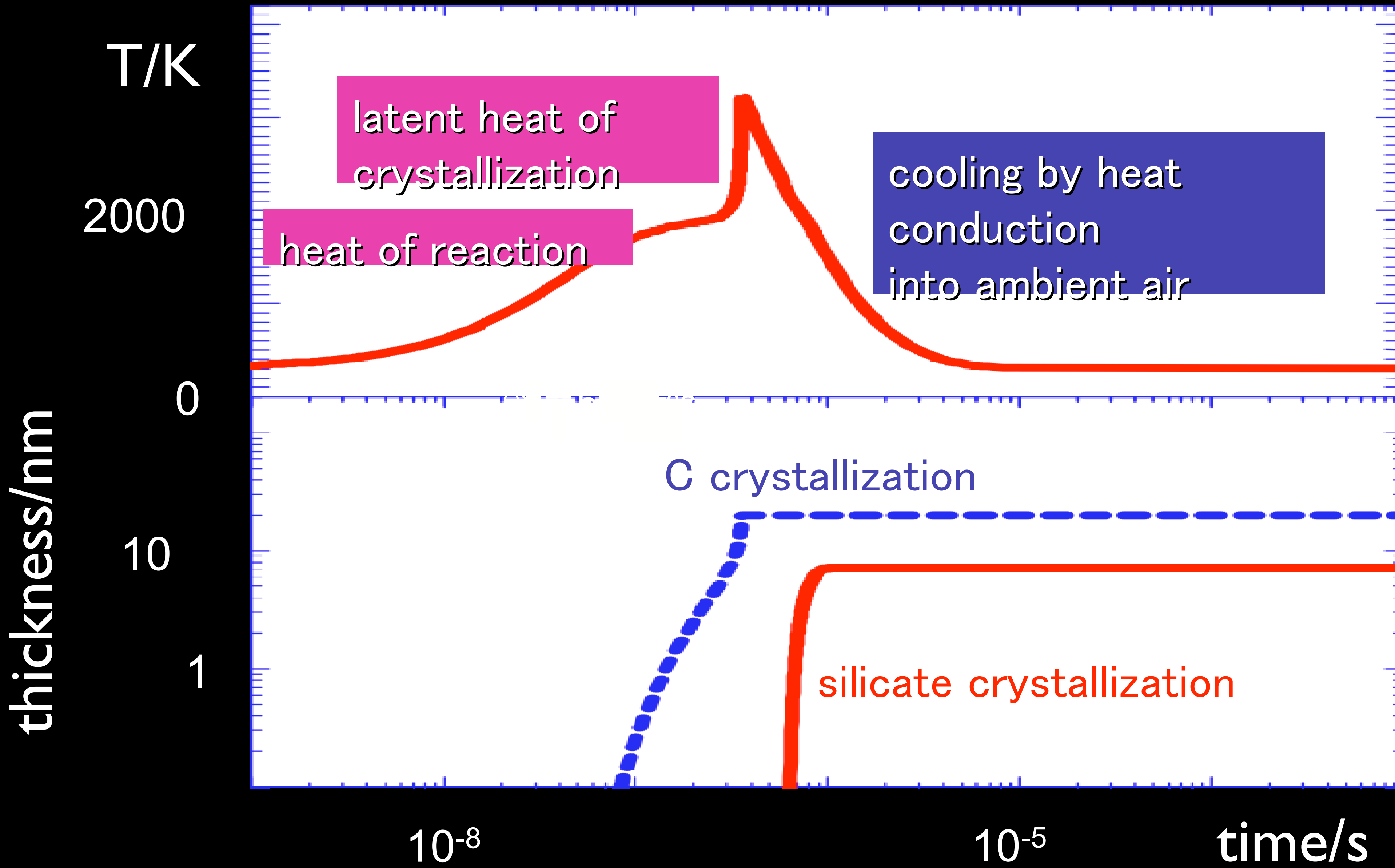
Rate of generation of heat of reactions in mantle

$$\dot{\varepsilon} = -\frac{dn_{\rm rad}}{dt}E_{\rm r} \qquad \frac{dn_{\rm rad}}{dt} = -\nu_{\rm r}e^{-E_{\rm ar}/kT}n_{\rm rad}$$

Crystal growth

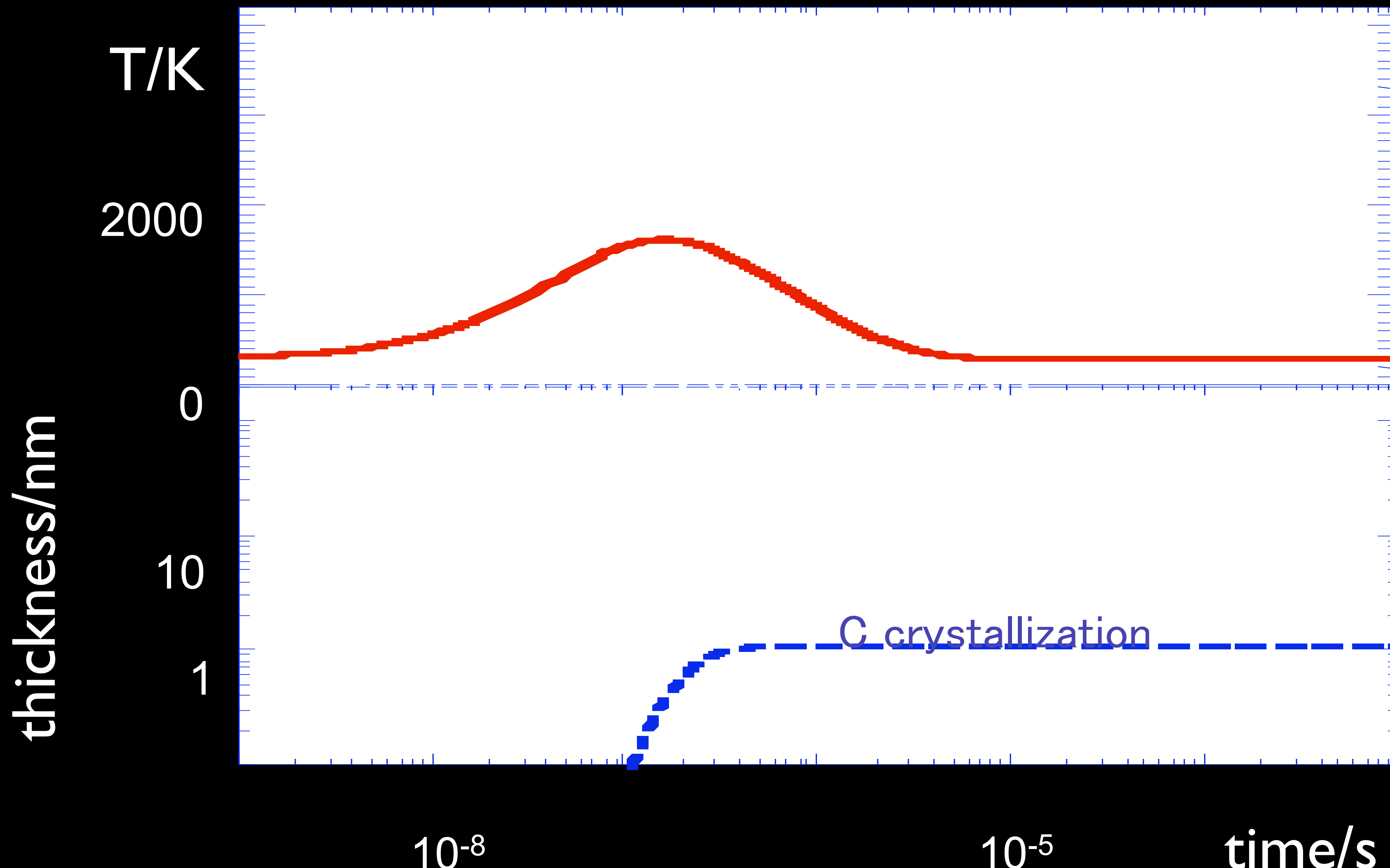
$$\frac{da_{\rm sil}}{dt} = a_0\nu e^{-E_{\rm sil}/kT}(1 - e^{-q_{\rm sil}(T_{\rm m}-T)/kT})$$

Feature of crystallization

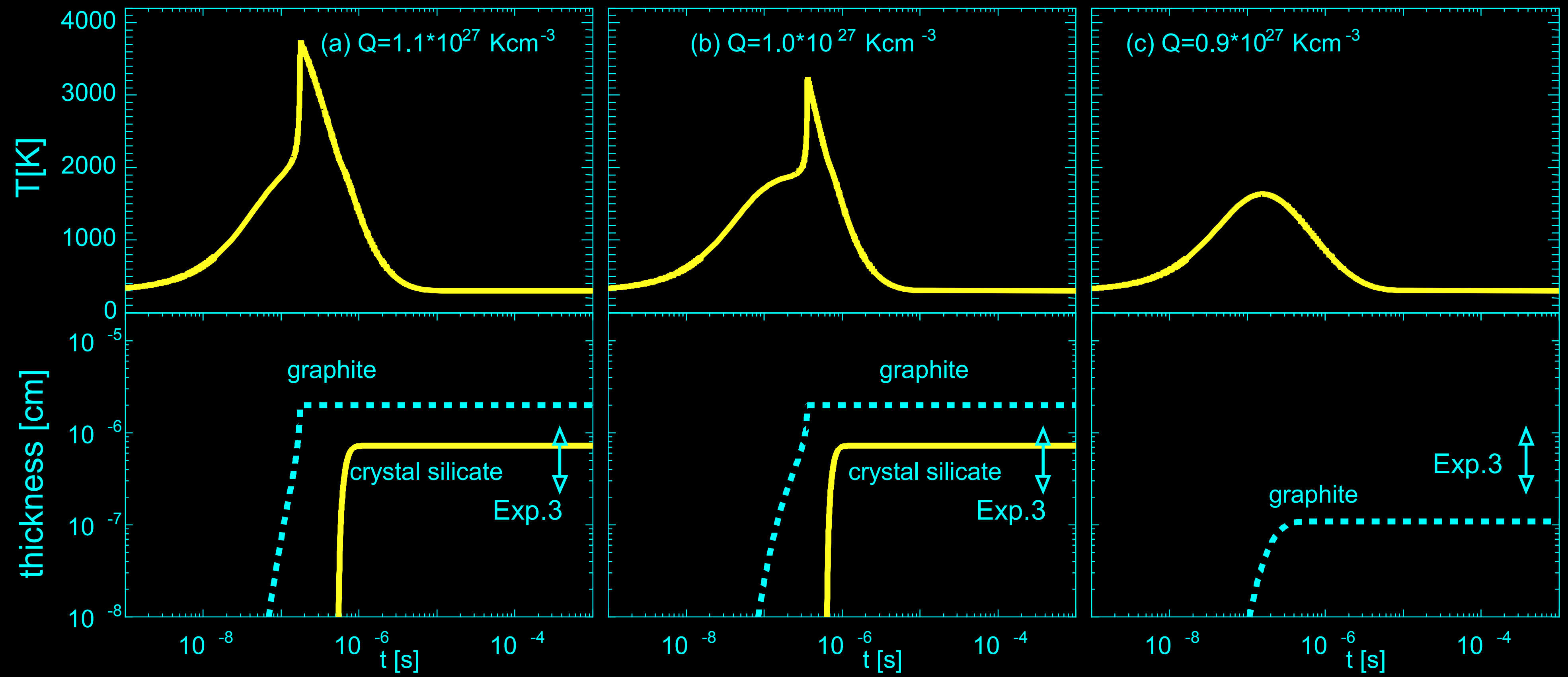


(n_{rad} (0) E_r =10^{27} K cm^{-3} ; tr = 10^{-8} s, gas density = 10^{-3} g cm^{-3} = 1 atm)

Feature of crystallization (2)
small deposition of heat of reaction

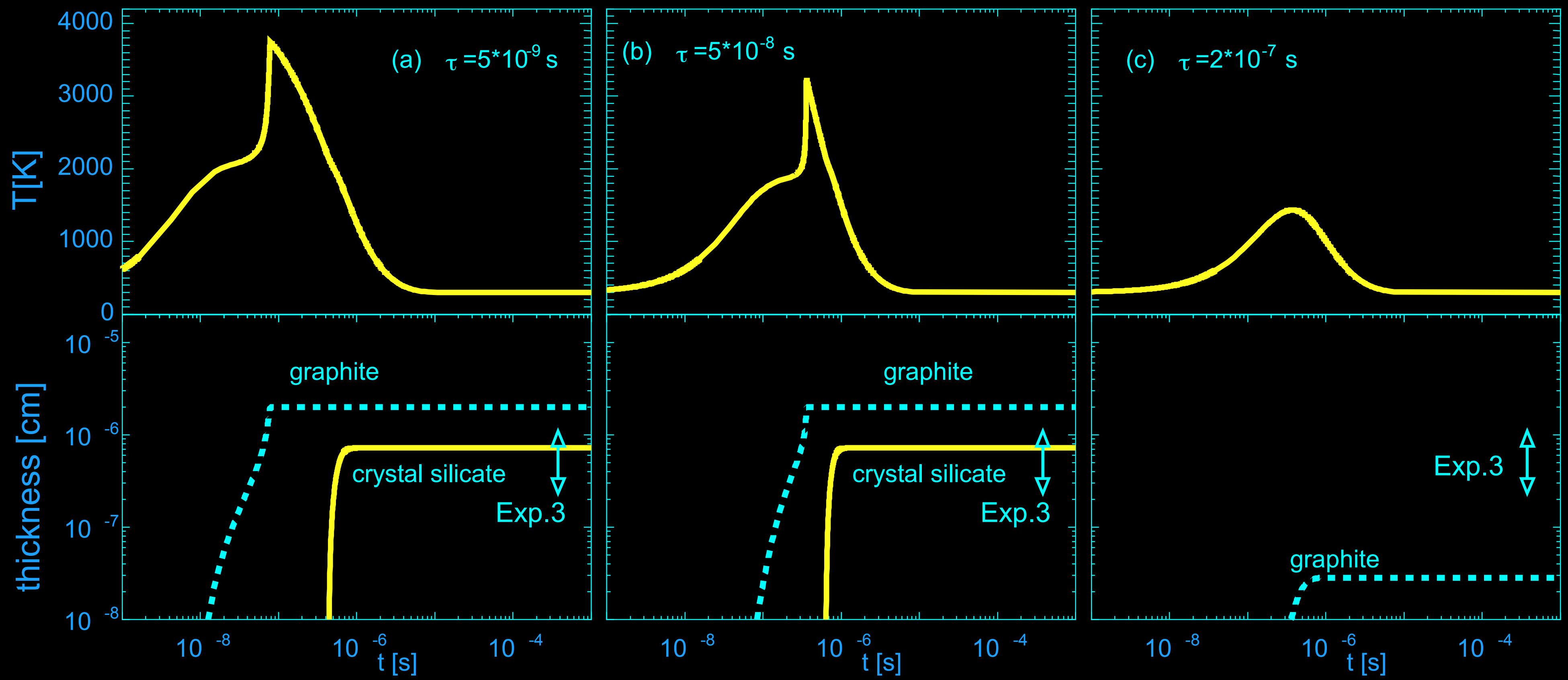


(n_{rad} (0) E_r = 0.9 ×10^{27} K cm^{-3} ; tr = 10^{-8} s, gas density = 10^{-3} g cm^{-3} = 1 atm)



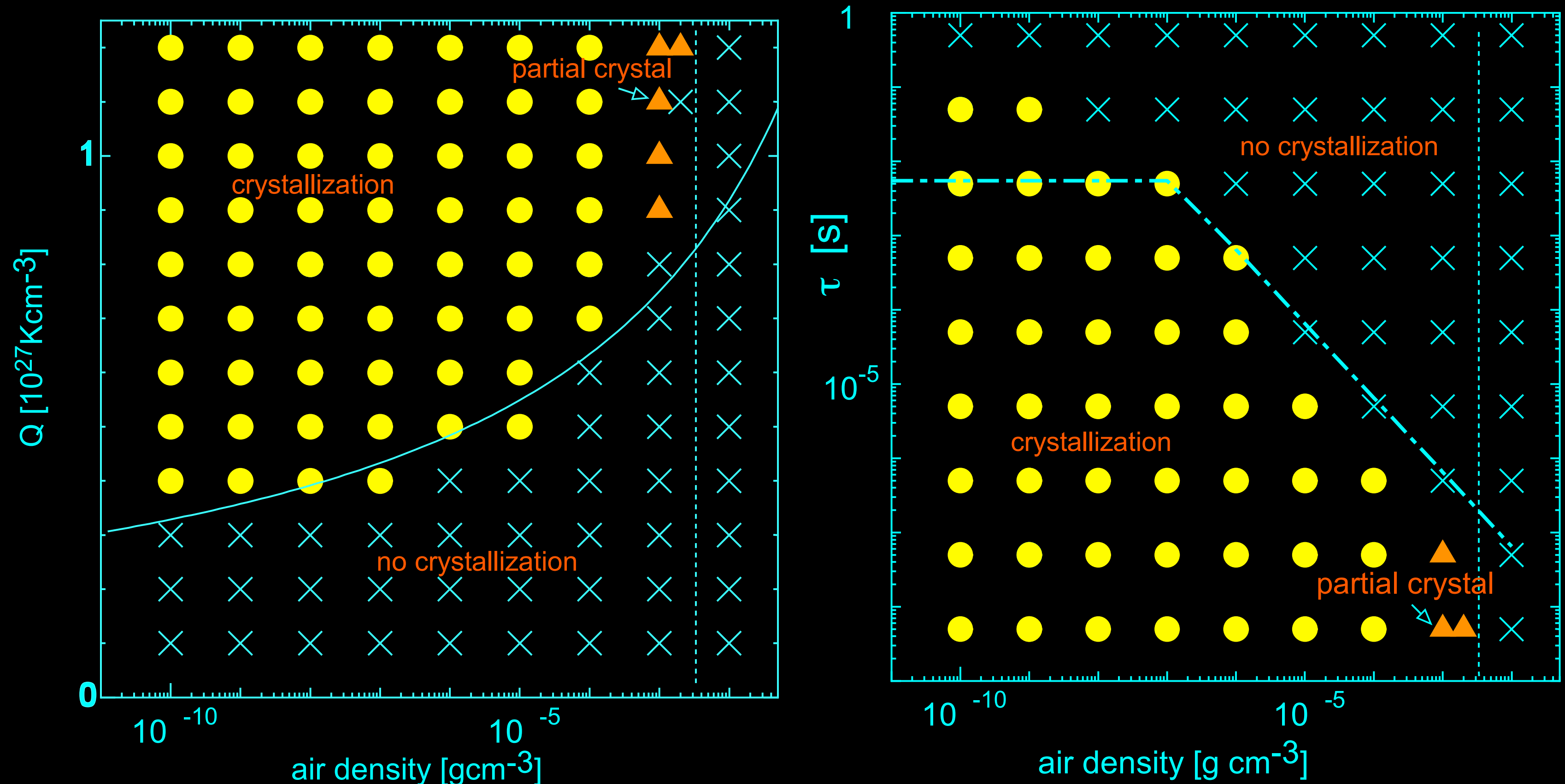
(a) Q=1.1*10^27 Kcm^-3
(b) Q=1.0*10^27 Kcm^-3
(c) Q=0.9*10^27 Kcm^-3
T[K]
4000
3000
2000
1000
0
thickness [cm]
10^-5
10^-6
10^-7
10^-8
graphite
crystal silicate
Exp.3
10^-8
10^-6
10^-4
t [s]

(P = 1 atm)


(a) τ =5*10-9 s
(b) τ =5*10-8 s
(c) τ =2*10-7 s
T[K]
4000
3000
2000
1000
0
thickness [cm]
10 -5
10 -6
10 -7
10 -8
graphite
crystal silicate
Exp.3
10 -8
10 -6
10 -4
t [s]

(P = 1 atm)

Crystallization conditions



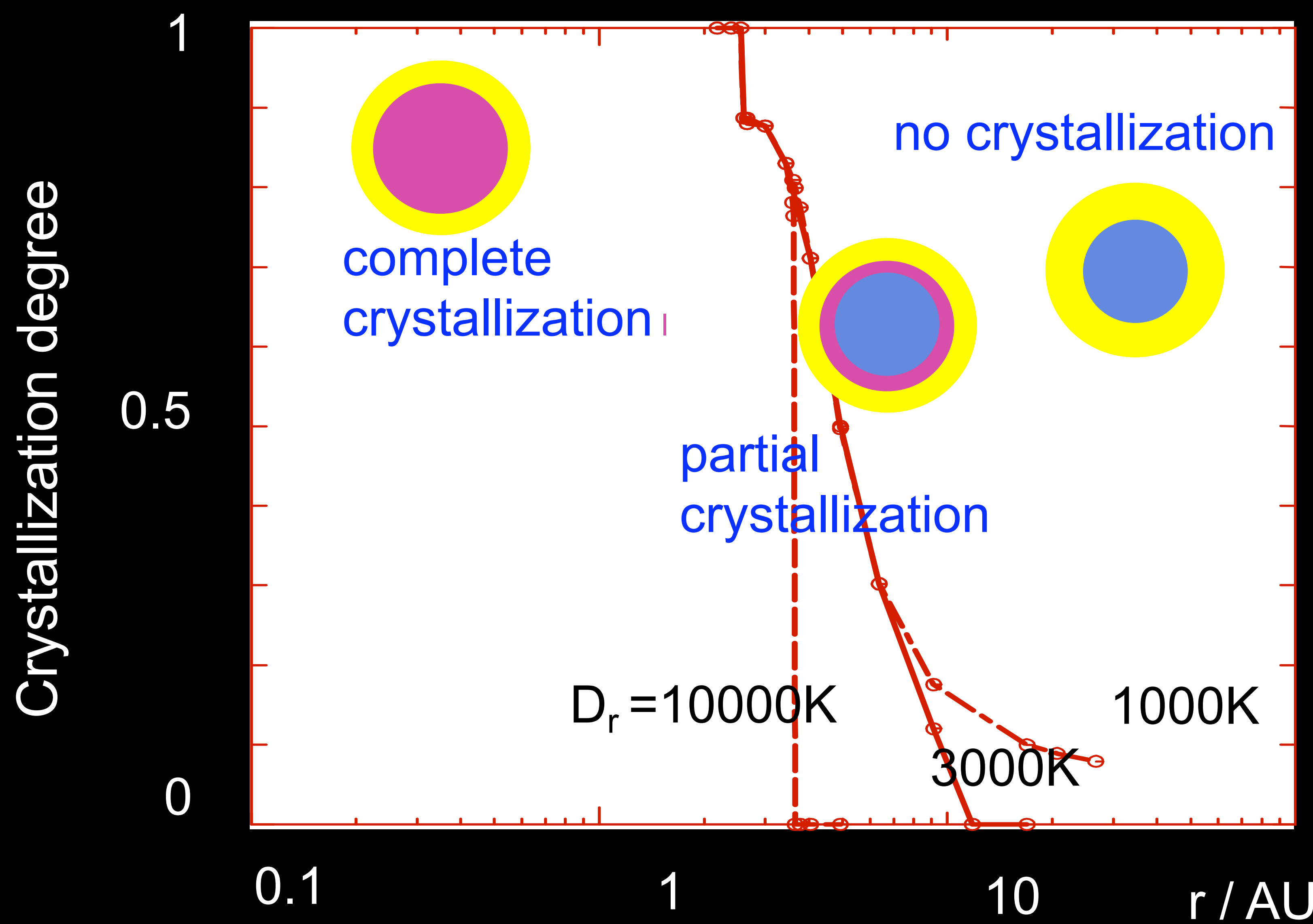
Low gas density, large energy deposition, fast reactions

→ easy crystallization

Radical concentration >1 - 10 % leads to substantial crystallization.

Crystallization degree in steady accretion disks

($n_{rad}(0)\ E_r = 10^{27}$ K cm^{-3})



Crystalline regions is much extended than by annealing.

Concluding remarks

- Crystallization triggered by chemical reactions may explain ubiquity of crystalline silicate in various objects
- Similarity of ice compositions in protoplanetary disks and comets:
  - Present mechanism can explain the coexistence of crystalline silicate and ice of IS composition in comets without mixing.
- Search for crystalline silicate at low temperature environments is encouraged by future high resolution observations of disks.

Concluding remarks

- The present mechanism does not depend on the details of the chemistry but depends only on the amount of reactive molecules times heat of reactions, $Q = n_{rad}(0)\, E_r$, and reaction timescale τ.
- Similar phenomenon
  - Wigner energy release known in nuclear reactor engineering
  - Sudden release of energy stored in graphite moderator irradiated by neutrons upon heating.

Concluding remarks

- The present mechanism does not depend on the details of the chemistry but depends only on the amount of reactive molecules times heat of reactions, $Q = n_{rad}(0)\ E_r$, and reaction timescale τ.
- Issues to be studied:
  - What triggers the crystallization? ambient temperature or others?
  - How realistic in space is the particle structure covered with a mantle including reactive molecules?