# Crystallization Mechanism of Cometary Grains

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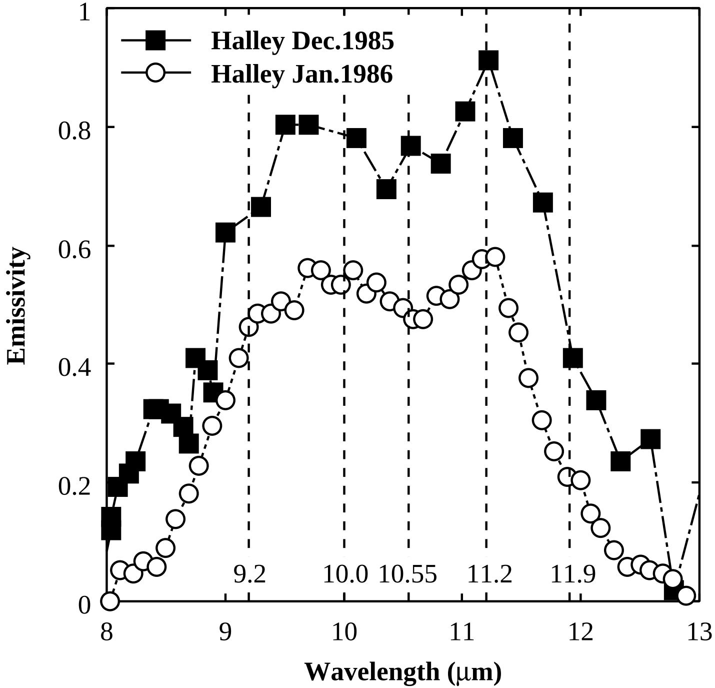
# Detection of crystalline silicate feature in C/Halley



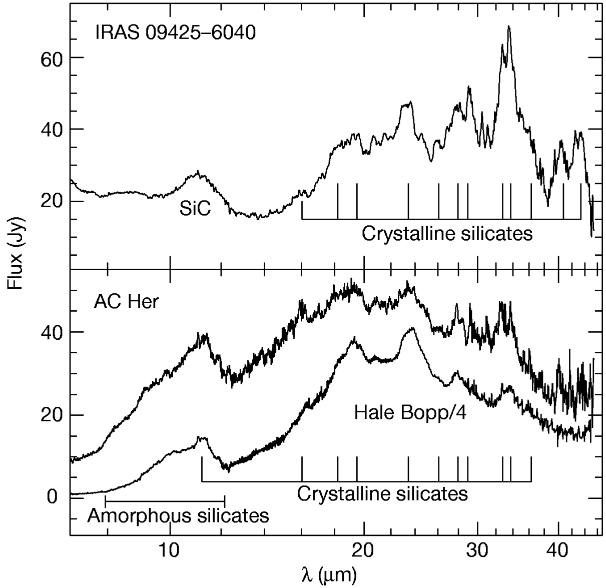

(Campins and Ryan 1989, Bregman et al. 1987)

- Similar features have been observed in several comets.

# Crystalline silicate in various kinds of objects

## Hanner 1999, 2003

1. Observed in
   - evolved stars
     - C-rich giant star, post-AGB star
   - YSOs at a late stage & young MS stars
     - Herbig Ae/Be stars & $\beta$-Pic
   - comets
   - ZL dust (Honda et al. 2003)
   - IDPs
2. Not observed in
   - ISM & molecular clouds
   - YSOs at an early stage




(Molster et al. 1999)

# Characteristics of crystalline silicate

- **Similar features**
- **Variety of objects: hot & cool**

# Origin of cometary silicate

## Mixture of amorphous & crystalline silicates

1. **amorphous: interstellar dust survived in the solar nebula**
2. **crystalline: annealing or condensation in the solar nebula**
   - **Need high temperature**

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## Present model:

- **“Cool” crystallization mechanism**
- **Need not mixing**

# Greenberg's model of cometary dust

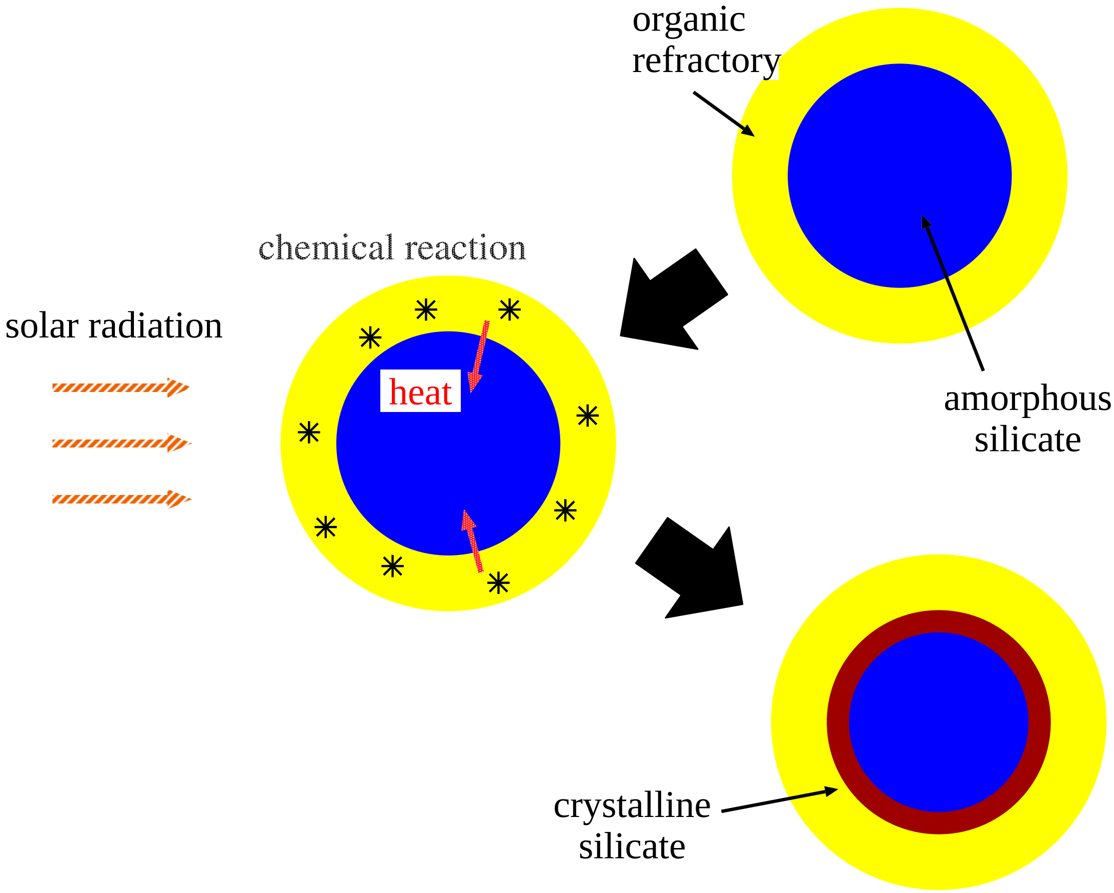
**silicate core + organic refractory (OR) + icy mantle**

# Crystallization mechanism

1. **Moderate heating of dust by solar radiation**
   - **Dust temperature (300 – 500 K) is not enough for silicate crystallization but enough for icy mantle sublimation**
2. **Trigger chain chemical reactions in the OR**
3. **Energy released by the reactions heats the silicate core.**
   - $E_{\mathrm{r}} \sim$ **several to 10 eV** $\sim 10^5$ **K**
4. **Lead to partial crystallization of the silicate core.**

**Chemical heating model**

# Chemical heating model



# Basic equations

## 1. Degree of crystallinity (Haruyama et al. 1993)

$$\frac{\partial f_c}{\partial t} = \frac{1 - f_c}{t_c} = \frac{1 - f_c}{A} e^{-E_c/kT}$$

- $t_c = Ae^{E_c/kT}$: crystallization time scale
- $E_c$: activation energy of crystallization
- $E_c = 3.5\,\mathrm{eV}$ for amorphous ol. and px. (Kimura et al. 2002)
  $A = 10^{-12}$ to $10^{-13}\,\mathrm{s}$

## 2. Temperature in the silicate core

$$\frac{\partial T}{\partial t} - \frac{\chi}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial T}{\partial r}\right) = \frac{H_c}{\rho c_p}\frac{\partial f_c}{\partial t}$$

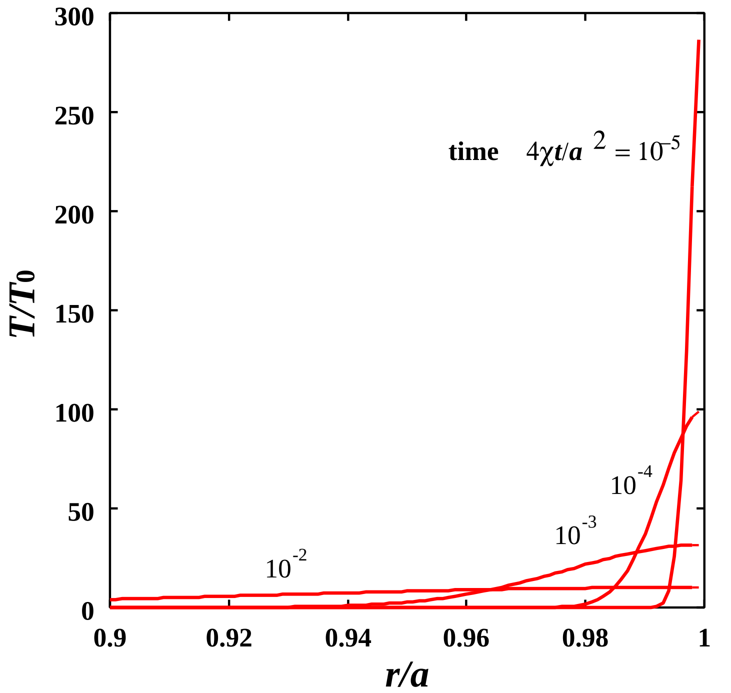
- $H_c$: Latent heat of crystallization per unit volume

# Initial condition

## Instantaneous heat source on the silicate core surface

- **Duration of heating of the surface due to reactions is short enough.**

# Temperature in the silicate core




**Substantial temperature increase near the core surface**

# Key parameter of crystallization

$$\theta_0 = \frac{k\Omega}{\mu m_{\mathrm{H}} c_{\mathrm{p}}} \frac{n_{\mathrm{r}} h_{\mathrm{r}}}{(\chi A)^{1/2}} \frac{E_{\mathrm{r}}}{E_{\mathrm{c}}}$$

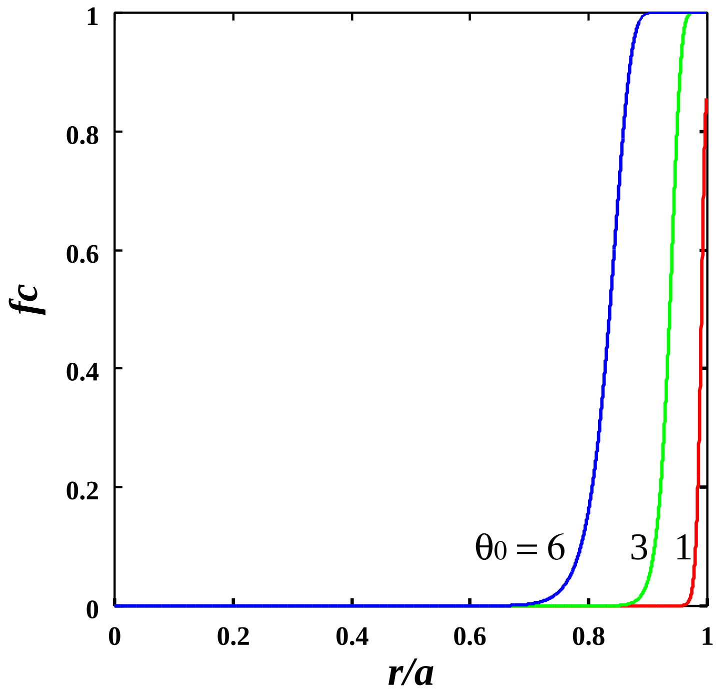
$\propto n_{\mathrm{r}}$ : density of reactive molecules in OR

## $\theta$-value determines crystallization degree

- crystallized volume ↗ as $\theta_0$ ↗
- Possible values of $\theta_0$ (Greenberg particle)

$$\theta_0 = 0.6 \text{ to } 6 \text{ for } n_{\mathrm{r}} = 10^{21} \text{ for } 10^{22}\,\mathrm{cm}^{-3}$$

# Volume fraction of crystalline region

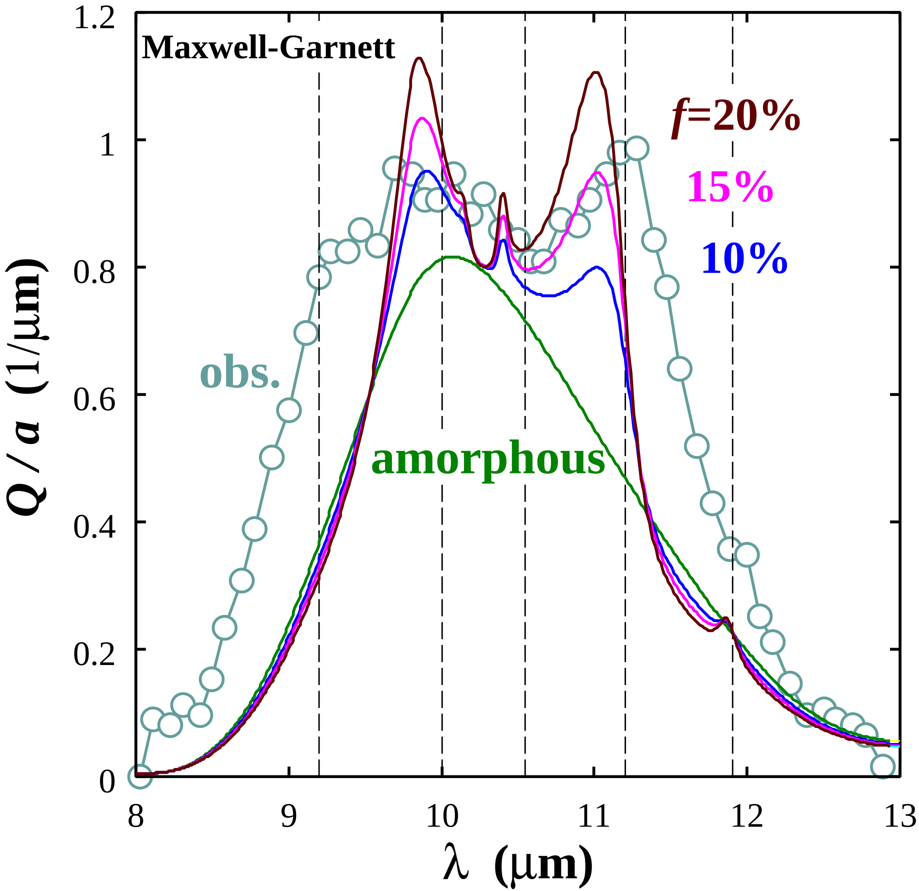



- **Substantial crystallization near the core surface for $\theta_0 > 1$**
- **volume fraction: 2 - 40 % for $n_{\rm r} = 10^{21}$ - $10^{22}\,{\rm cm}^{-3}$**

## Does the crystalline fraction explain the observed spectra?

1. **Calculations of the spectra**
   - **individual grain: am. core + xtal. mantle structure**
   - **Spectra of aggregates: MG in the Rayleigh regime**
   - **varying volume fraction of the crystalline region**
2. **Optical const ($n$, $k$) data for $Mg_2SiO_4$**
   - **amorphous: Scott & Duley 1996**
   - **crystalline: Sogawa et al. 1999**

# Spectra vs volume fraction of crystalline forsterite



# Comparison with observed spectrum

- **Crystalline volume fraction $f$ of 10 – 20 % can reproduce the observed crystalline feature.**
  - **$f$-value: within the range expected from the chemical heating model**
  - **best fit: $f \simeq 15\,\%$**
- **Detailed fitting is another problem.**
  - **mixing pyroxene & other materials**
  - **varying Mg/Fe ratio**
  - **grain size distribution**
  - **particle shape**

# Conclusions

1. Chemical heating mechanism works.
   - Crystallization degree ($\sim$ 15 %) needed to explain the observed spectra can be realized.
2. Chemical heating model
   - Need not high temperature and mixing of amorphous & crystalline silicate
   - Preserve ices of interstellar composition
   - Applicable to crystallization in protoplanetary disks & other objects
   - Amount of energy deposition in the OR is a key quantity.

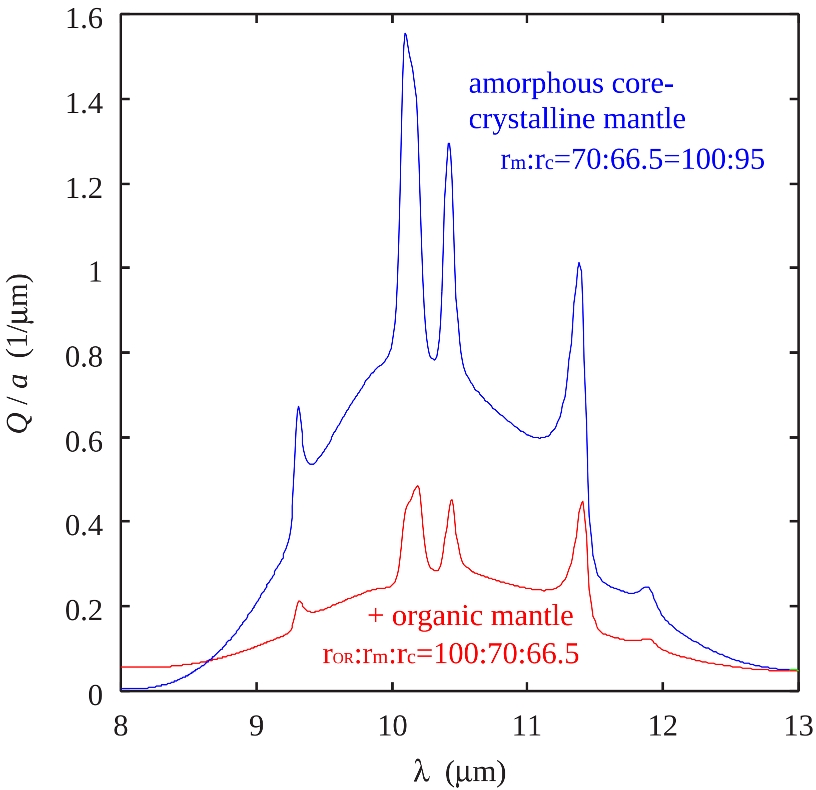



Figure 1: Effect of the outer organic mantle on the spectrum. The blue curve shows $Q/a$ of a small sphere composed of an amorphous forsterite core and a crystalline forsterite mantle, and the red one shows $Q/a$ adding an organic outer mantle. Optical constant data of the organic mantle are adopted from Greenberg & Li (1996) A&A 309, 258.

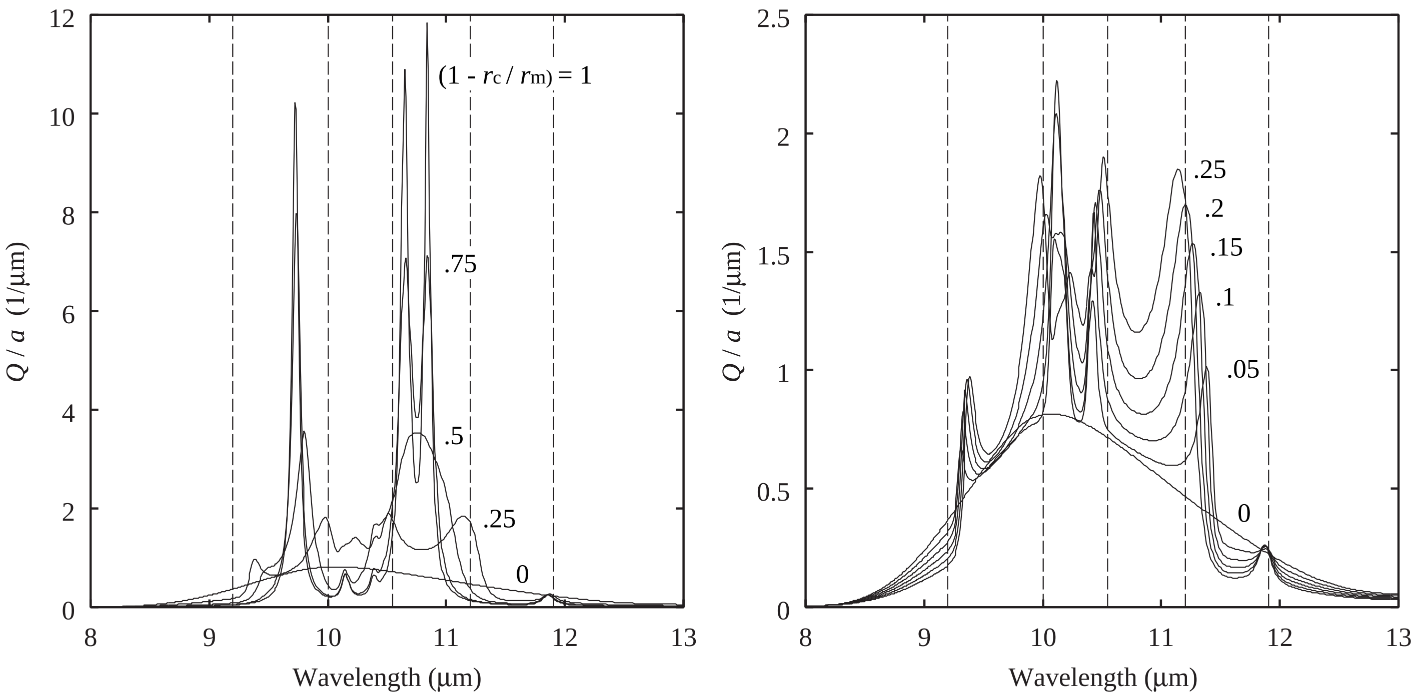



Figure 2: $\boldsymbol{Q/a}$ for amorphous core-crystalline mantle silicate small spheres. Amorphous forsterite ($Mg_2SiO_4$) from Scott & Duley (1996) ApJS 105, 401 core- crystalline olivine ($Mg_2SiO_4$) from Sogawa et al. (1999) ISAS LPS 32, 179 mantle grains.