Thermal Processing of Dust Particles in the Protoplanetary Disks

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Message: **Flash heating of dust particles in the disk**
should be taken into account when we think of
the structure and evolution of the protoplanetary disks.
Heating of Dust Particles in the Disk
Thermally Processed Dust Particles in Early Solar System/TTS, HAeBe

- **Chondrules**
  - sub mm-sized silicates
  - heated and molten
  - meteorites in solar system

- **Crystalline Silicates**
  - micron-sized silicates
  - heated and annealed
  - disks around TTS/HAeBe, and comets
Chondrules
- sub mm-sized spherical silicates in meteorites
- dominant component (up to 80% of all the meteorites)
- formed in TTS phase
  - age differences among chondrules ~ 2 Myr
- once molten
  - peak temperature ~ 2000 K
  - duration ~ minutes
  - heating rates > $10^4$ K/hr
  - cooling rates ~ 100 - 1000 K/hr
- multiple heating

Proposed Forming Mechanisms --- "Flash Heating"
- Shock-Wave Heating
- Lightning
- (X-wind --- X)
Shock-Wave Heating Mechanism

and

Chondrule Formation
Shock–Wave Heating Mechanism

heating by drag & conduction from hot gas
$V_s = 10 \text{ km s}^{-1}, \ n_{\text{pre}} = 10^{14} \text{ cm}^{-3}, \ a_0 = 0.1 \text{ mm}$

Iida, Nakamoto, Susa, & Nakagawa (2001) Icarus 153, 430
Conditions of Shock Waves for Dust Melting

\[ \log_{10} n_0 \text{ [cm}^{-3}] \]

\[ \text{atm} \]

\[ a_0 = 0.1 \text{ mm} \]

\[ V_s \text{ [km s}^{-1}] \]

Iida, Nakamoto, Susa, & Nakagawa (2001) Icarus 153, 430
Shock-Wave Heating Model for Chondrule Formation

- Peak Temperature
- Duration
- Cooling Rates
- Heating Rates
  (Tachibana, Huss, Miura, & Nakamoto 2004)
- High Pressure
  (Miura, Nakamoto, & Susa 2002)
- Size (Maximum)
  (Susa & Nakamoto 2002)
Annealing of Dust Particles
Crystalline Silicates in TTS, HAeBe, and Comets

- small dust particles (~ 1 μm)
- annealed in the disk

Heated and annealed by shock-wave heating?


for crystalline silicates in various environments
e.g., TTS, HAeBe, Solar Nebula, post-AGB, ...
Evaluation of "Crystallization"


Experiments of magnesium silicate annealing

![Graph showing SEI as a function of T and t]

**SEI: a function of T and t**

SEI > 100 --- crystalline, SEI < 100 --- amorphous
Thermal History of a Small Particle

\[ V_s = 10 \text{ km s}^{-1}, \quad n_{\text{pre}} = 10^{11} \text{ cm}^{-3}, \quad a_{\text{gr}} = 1 \mu\text{m} \]

Peak Temp. \( \sim 1150 \text{ K} \)
Duration \( \sim 40 \text{ sec for } > 1100 \text{ K} \)

Finally, \( \text{SEI} \sim 5.5 \times 10^3 \) (crystallized)
Conditions of Shock Waves for Crystallization

$V_s \text{ [km s}^{-1}]$

$\log_{10}(n_{pre} \text{ [cm}^{-3}]$

- $a_{gr} = 1 \mu m$
- $a_{gr} = 0.1 \mu m$

Strong Shocks
Complete Evaporation
Weak Shocks
No Crystallization

Nakamoto & Miura, submitted
Annealing by Accretion Shock

Mass accretion rate: $\dot{M} \sim 10^{-5} \, M_{\text{sun}} \, \text{yr}^{-1}$
Velocity: $v_{\text{ff}} \sim 40 \, (R/1\,\text{AU})^{-1/2} \, \text{km} \, \text{s}^{-1}$
Uniform accretion

Ram Pressure = Static Pressure
$n \sim 10^{10} \, \text{cm}^{-3}$

Annealing Region
1 $\mu$m particles: $R \sim 1 - 4 \, \text{AU}$
0.1 $\mu$m particles: $R \sim 3 - 20 \, \text{AU}$
Source of the Shock Waves
Sources of Shock Waves

- Spiral Density Waves in Self-Gravitating Disk
- Bow Shocks in front of Eccentric Planetesimals
- Accretion Shock
- Shock Waves Induced by X-Ray Flare Winds

(Nakamoto, Kita, Tachibana, & Hayashi 2004)
Shock Waves Induced by Winds from X-Ray Flares

X-Ray Flares  Winds  Shock Waves

Hayashi et al. (1996)

Feigelson et al. (2002)
Places of Shock Fronts

Ram Pressure of Winds = Static Pressure of Disk
\[ \alpha = 10^{-3} \]

Takeuchi & Lin (2002)
Advantages of the model

in addition to basic features of Shock-Wave Heating Mech.,

• clear source of shock waves
• time scales of chondrule formation
• age differences among chondrules
• chemical fractionation-age relation
• low concentration of precursor particles
• longer stopping time -> lower cooling rate
• ...
Dust particles in the disk are heated by some heating events. e.g., chondrules, crystalline silicates

Shock wave heating is a promising mechanism for chondrule formation and dust annealing.

Winds from X-ray flares may generate appropriate shock waves at the upper region of the disk.

Dust particles in the upper region of the disk may provide important information on the thermal processing of dust particles in the disk.