均質核形成によるダスト生成実験と古典的核形成論

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Why nucleation?

- Number
- Morphology
- Habit
- Size
- Size distribution

Not only industrially,
✓ Nucleation is also important to know the formation process of Cosmic dust particles.

We need understand Nucleation!
99% gas, but 1% solid

nm sized particles

Building block of Planetary system & Life

Credit of all photos: NASA/JPL/Space Science Institute
99% gas, but 1% solid \( \text{nm sized particles} \)

Building block of Planetary system & Life

Nozawa, et al., 2009.

Molster et al., 2002

99% gas, but 1% solid
Condensation temperature of major elements as a function of C/O ratio.

Constraints on the formation conditions and environment have been calculated. 
(Lodders & Fegley 1995; Sharp & Wasserburg 1995; Chigai et al. 1999, 2002)

Condensation sequence
Sizes of core-mantle

C/O abundance ratio
Total gas pressure
Gas outflow velocity
Stellar mass loss rate
Smoke generator

Nickname is now wanted!

TASHIROS
The Absolute Smoke generator and Hi diffusion Interferometric Rapid Observation System
Smoke generator + Interferometer
Smoke generator + Interferometer
- He/Ne laser
- Camera
- Mirror
- Beam splitter
- Objective lens, pinhole, collimate lens
- IR filter
- Polarizer
- Band-pass filter
- Pyrometer
- ND filter
- Objective lens, pinhole, collimate lens
- Mirror
- Lens
- IR filter
- Dichroic mirror

Wavelength: 632.8 nm
He/Ne laser

Objective lens, pinhole, collimate lens

Camera

Mirror

Beam splitter

Objective lens, pinhole, collimate lens

Camera

ND filter

Band-pass filter

Pyrometer

Lens

IR filter

Dichroic mirror

Mirror

Polarizer

ND filter

632.8 nm
The diagram illustrates a setup with several optical components:

- **He/Ne laser**
- **Objective lens, pinhole, collimate lens**
- **900 mm**
- **600 mm**
- **Camera**
- **Mirror**
- **Beam splitter**
- **Objective lens, pinhole, collimate lens**
- **ND filter**
- **Band-pass filter**
- **Polarizer**
- **IR filter**
- **Pyrometer**
- **W wire 0.3 mm**
- **70.0 mm**
- **Dichroic mirror**

The setup includes a laser source at 632.8 nm, with various optical elements configured to direct and manipulate the laser beam.
Interferogram

Temperature: 298 K (25°C)
Gas: Ar $1 \times 10^4$ Pa
Refractive index: 1.00002714

Temperature: 323 K (50°C)
Gas: Ar $1 \times 10^4$ Pa
Refractive index: 1.00002503

Heating

Difference of refractive index is only $2 \times 10^{-6}$. 
Interferogram

Temperature: 298 K (25°C)
Gas: Ar $1 \times 10^4$ Pa
Refractive index: 1.00002714

Temperature: 323 K (50°C)
Gas: Ar $1 \times 10^4$ Pa
Refractive index: 1.00002503

We can detect only a difference of $10^{-6}$-$10^{-7}$ orders!!

Thermo couple 0.1 mmΦ

Pyrometer

Thermocouple
Temperature: 298 K (25°C)
Gas: Ar $1 \times 10^4$ Pa
Refractive index: 1.00002714

Temperature: 298 K (25°C)
Gas: Ar $9 \times 10^3$ Pa, O$_2$ $1 \times 10^3$ Pa
Refractive index: 1.00002703

Only Temperature

Temperature & concentration

Temperature information is subtracted by oxygen free experiment.
A tungsten wire (0.3 mmφ and 70 mm depth) is heated in a mixture gas of Ar (9 × 10³ Pa) and O₂ (1 × 10³ Pa).
1st, 2nd and 3rd fringes correspond to 320, 500 and 1150 K, respectively.
In-situ observation using interferometer

- WO\textsubscript{3} particles are condensed 700 K lower than equilibrium T due to homogeneous nucleation!

- Nucleation occurs below the evaporation source.

- Degree of supersaturation is at least 10\textsuperscript{11}!!

- Evaporation Source
  - $P_e=1.3 \times 10^3$ Pa at 1570 K
  - Position of Smoke
  - $P_e=\sim10^{-9}$ Pa at 870 K
Convection current and Smoke

The heated source generated a high-temperature atmosphere and convection currents (~100 cm s⁻¹).

Evaporated WO₃ vapor diffuses in uniformly with 9.79 cm² s⁻¹.

Since there is a strong convection current, rising vapor is accelerated and down flow is restrained.

As the result, concentration of WO$_3$ vapor is getting higher below the evaporation source.
Finally, nucleation occurs at the highest supersaturation environment between convection current of ambient gas and evaporated WO₃ vapor.

Nuclei follow the convection current and grow to make nanoparticles in smoke.
Convection current and Smoke

- WO$_3$ vapor
  - Diffusion velocity: 95 cm s$^{-1}$
- Convection current of ambient gas: ~100 cm s$^{-1}$

Finally, nucleation occurs at the highest supersaturation environment between convection current of ambient gas and evaporated WO$_3$ vapor.

Nuclei follow the convection current and grow to make nanoparticles in smoke.

We can derive a lot of information from Interferogram.
Condensation temperature of major elements as a function of C/O ratio.

The condensation sequence is as follows:
- Cor. Corundum, Al₂O₃
- Per. Periclase, MgO
- Gehl. Gehlenite, Ca₂Al(AlSi)O₇
- Sp. Spinel, MgAl₂O₄
- For. Forsterite, (Fe,Mg)₂SiO₄
- Fe Iron, Fe

Constraints on the formation conditions and environment have been calculated.
(Lodders & Fegley 1995; Sharp & Wasserburg 1995; Chigai et al. 1999, 2002)

Condensation sequence
Sizes of core-mantle
C/O abundance ratio
Total gas pressure
Gas outflow velocity
Stellar mass loss rate

0.5 µm
Croat et al., 2004 LPS, 1353.
Conclusion

- Temperature and concentration can be measured in-situ during smoke experiment.
- Condensation occurs under very high supercooling ($\Delta T=\sim 400-700$K).
- Nucleation takes place below evaporation source in smoke experiment.
- Nucleation theory may be verified.