LABORATORY EXPERIMENTS ON THE EFFECT OF GAS SPECIES FOR EARLY DUST FORMATION

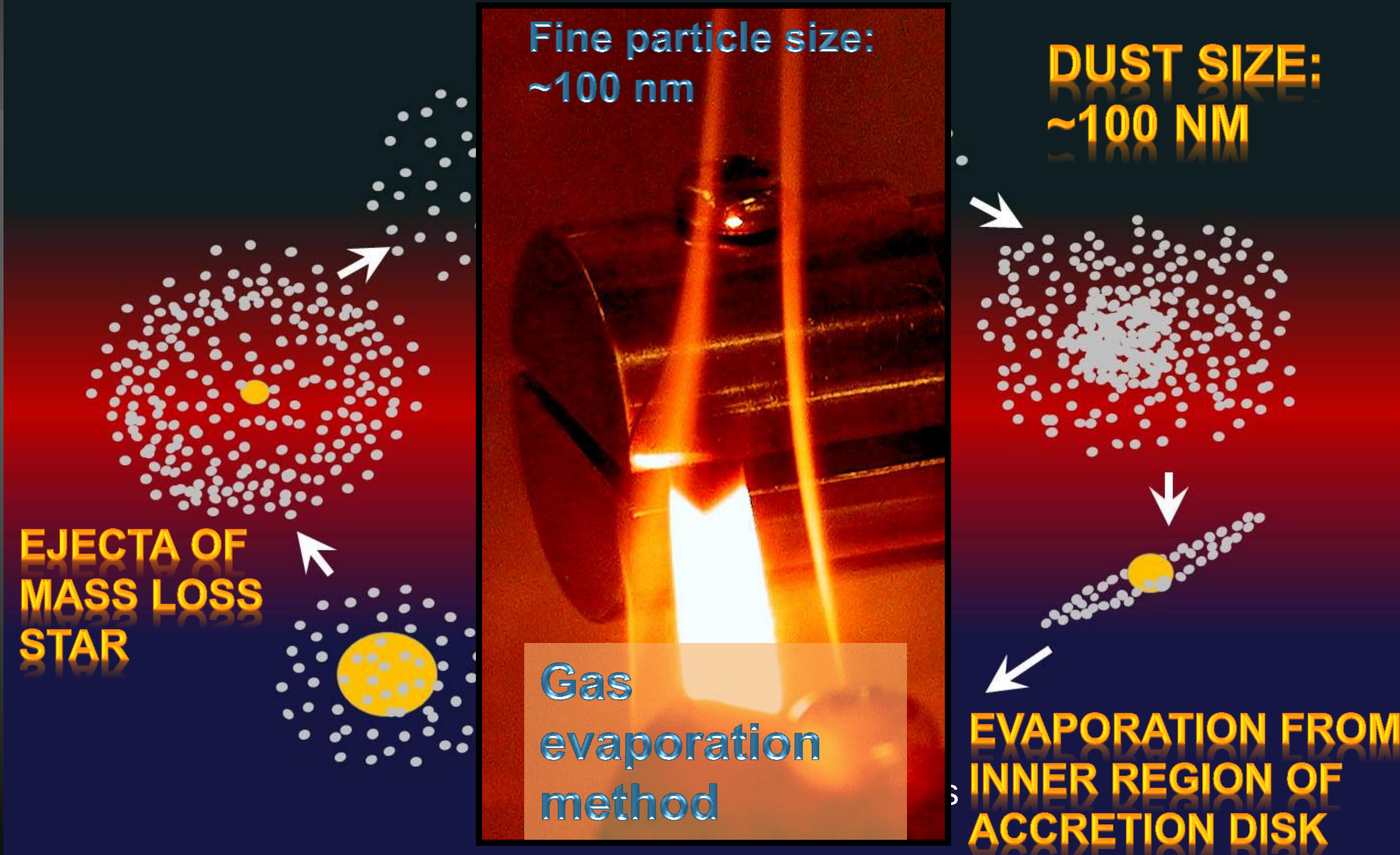
Akihito Kumamoto, Tetsuya Miyashita,
Chihiro Kaito and Yoshio Saito

Ritsumeikan University

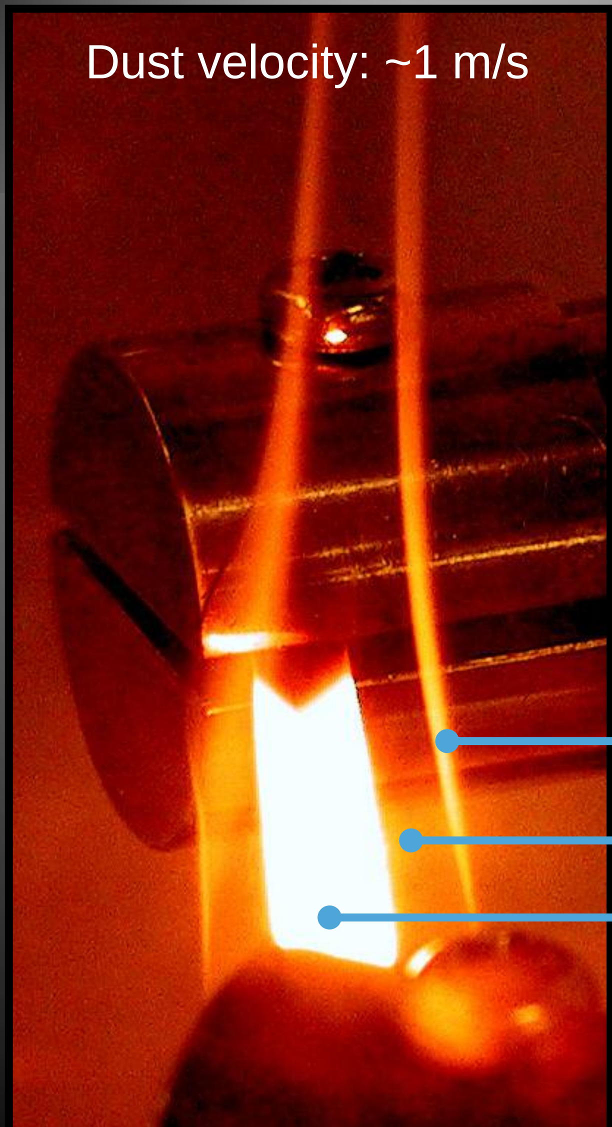
The workshop held from September 27 to October 1, 2010 at the Friedrich Schiller University Jena, Germany

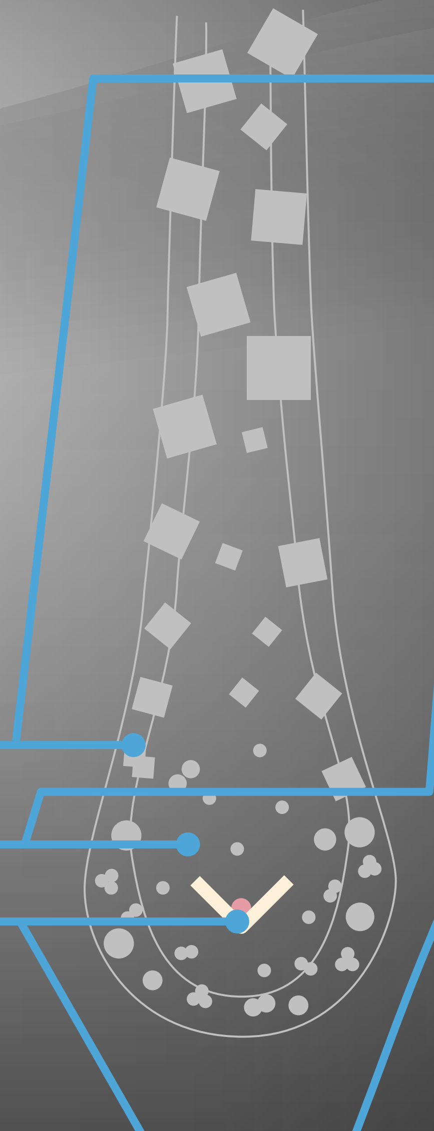
A study focusing on early stage of dust formation: Gas to Solid

Dust as a bearer of material circulation



Gas evaporation method





Dense Smoke Region:

Coalescence growth

Solid-solid reaction took place in the convective environment.

Around the source:

Vapor condensation

by collision between evaporated species and ambient gas

Evaporation source:

Gaseous emission

An evaporant is heated upon a temperature.†

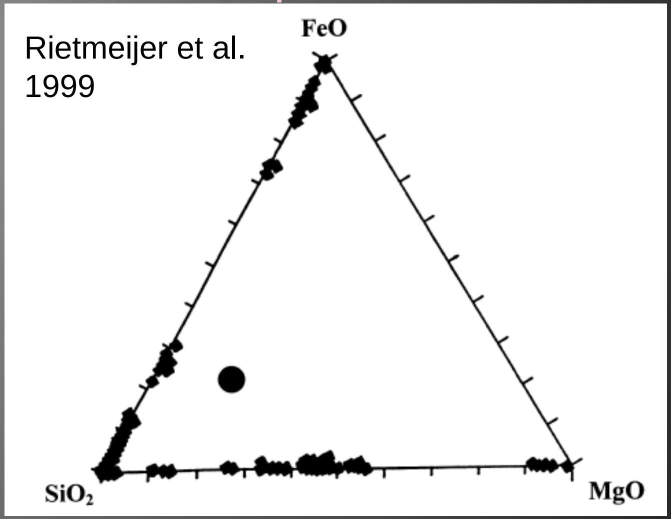
† This is empirically known as the temperature of which vapor pressure of the evaporant becomes 133 Pa.

Gas to solid
Condensation smoke experiments
can create the supersaturated gas required for homogeneous nucleation.

FORMATION OF SILICATE DUSTS

- Interflow of Mg-SiO smoke
  [Day and Donn 1978]
- Condensation flow apparatus
  Mg-Fe-SiO-H_2-O_2
  [Nuth et al. 1988; 1999]
  [Rietmeijer et al. 1999]
- Laser ablation on Silicate
  [Fabian et al. 2000]

Variable composition of silicate dust



Variation of formation mechanism is indicated in an experiment.

More precise separation of the condensation condition is required for understanding the production of various compounds.

Material: Silicon oxide

- Observation of Silicon oxide
  - Possibly existence of the silica (SiO_2; within various structure) dusts has been suggested by T Tauri stars.
    [B. A. Sargent et al., 2009]
  - Silica is not seen in the interstellar medium.
    [Li & Draine, 2002]
- Stability
  - Presumable producing mechanism

$$Mg_2SiO_4 + SiO_2 \leftrightarrows 2MgSiO_3$$

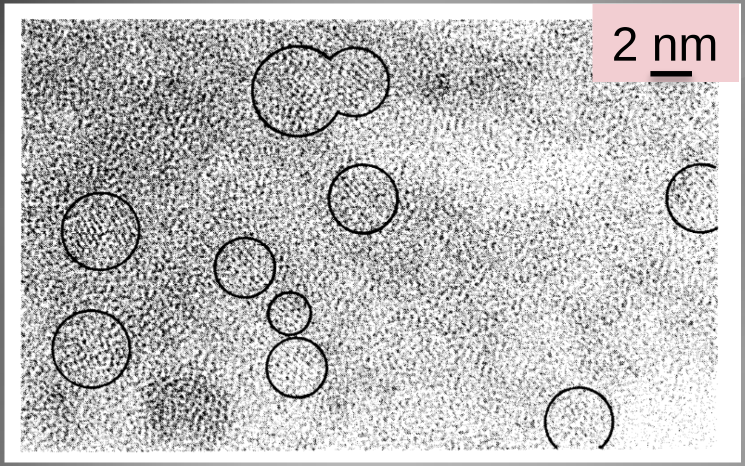
$> 1800K$

SiO is one of the most stable species at high temperature and at vacuum condition.

The stability of SiO species may affect the material circulation with silicate.

An understanding of silicon monoxide: A compound of Si and SiO_2 crystallite

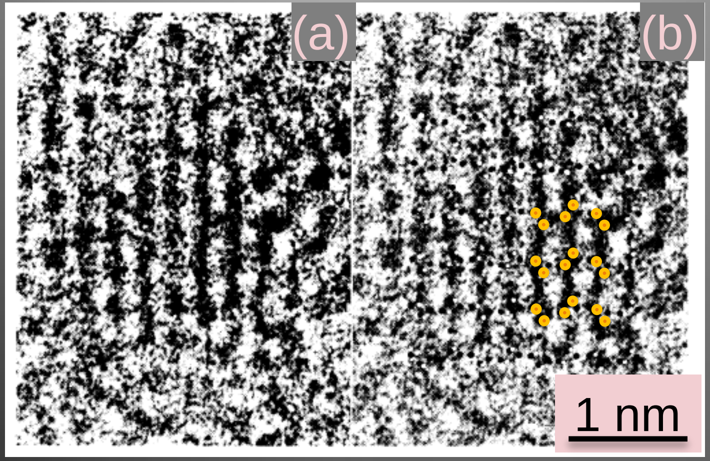
Kaito and Shimizu 1984



The film obtained by evaporating SiO powder
Thickness: 8 nm

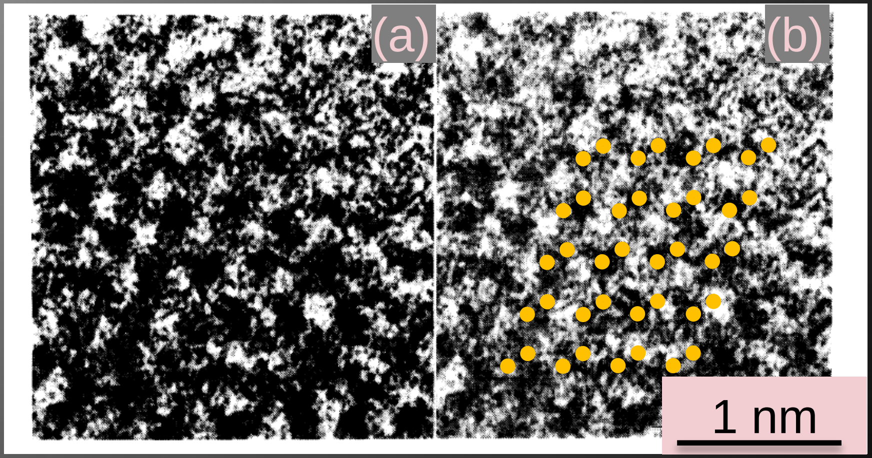
High resolution transmission electron microscopic image shows crystallites of α-cristobalite and silicon.

[0$\bar{1}$1] projection of α-cristobalite



(b) Open circles denoted silicon atoms.

[0$\bar{1}$1] projection of silicon



The (111) projection of Si crystal is inserted in (b) by solid circles.

Note: The sample below ~10 nm in thickness is required to observe ~1 nm sized crystallite under the HRTEM condition.

An understanding of silicon monoxide: A compound of Si and SiO_2 crystallites

Morioka et al. 1997

Heating at the air condition

Peak shifts take place by phase transformation of SiO_2.

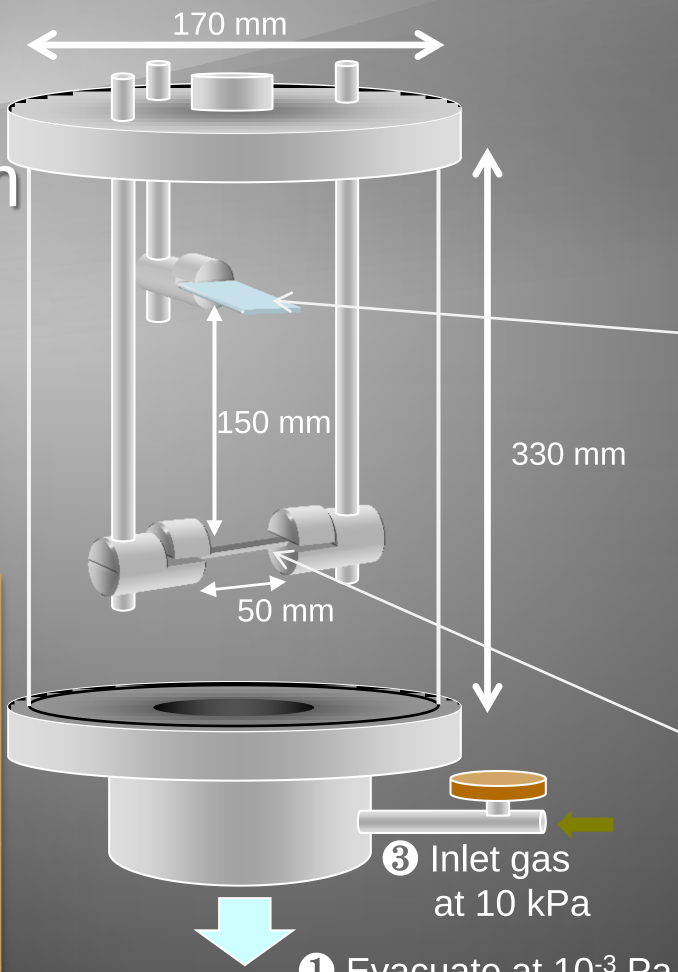
Table 1. Absorption peak positions from IR spectra.

Sample	Absorption peak positions (μm)			Composition of microcrystallite
Commercial SiO powder	9.2	12.5	21.3	Fused silicon and fused quartz
As-deposited SiO film	10.2	13.5	19.5	Silicon and α-cristobalite
300°C-heated film	9.6	11.4 12.5	22.5	Silicon and β-cristobalite
As-prepared SiO grains	9.2	11.4 12.7	21.8	Silicon and β-cristobalite
300°C-heated grains	9.2	11.4 12.4	21.5	Silicon and β-cristobalite
500°C-heated grains	9.0	12.5	21.0	α-quartz
Vibration corresponding to absorption peaks	Si-O stretching	Si-Si streching†	O-Si-O bending	

† Si-Si stretching is synonymous with Si-O-Si symmetric stretching vibration in the crystal [Lippincott, et al., 1958].

Examination of stability of SiO during dust formation

8L vacuum chamber

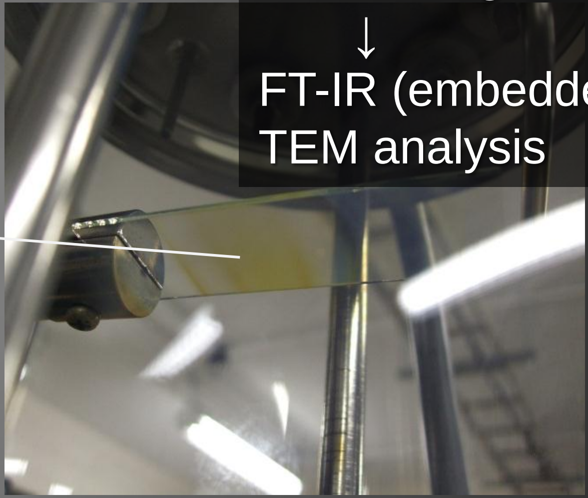


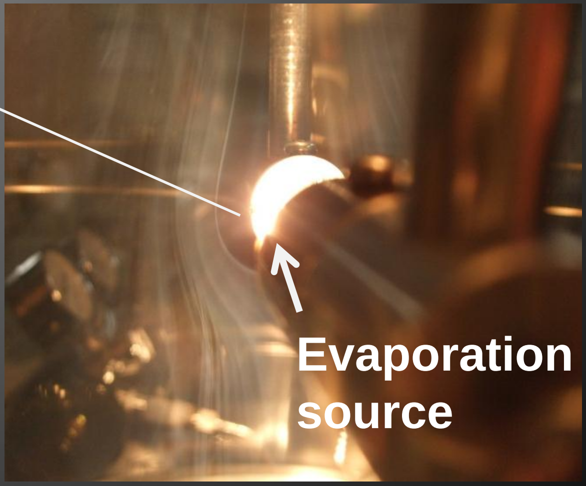
Smoke grains collected on a slide glass

↓

FT-IR (embedded KBr)

TEM analysis



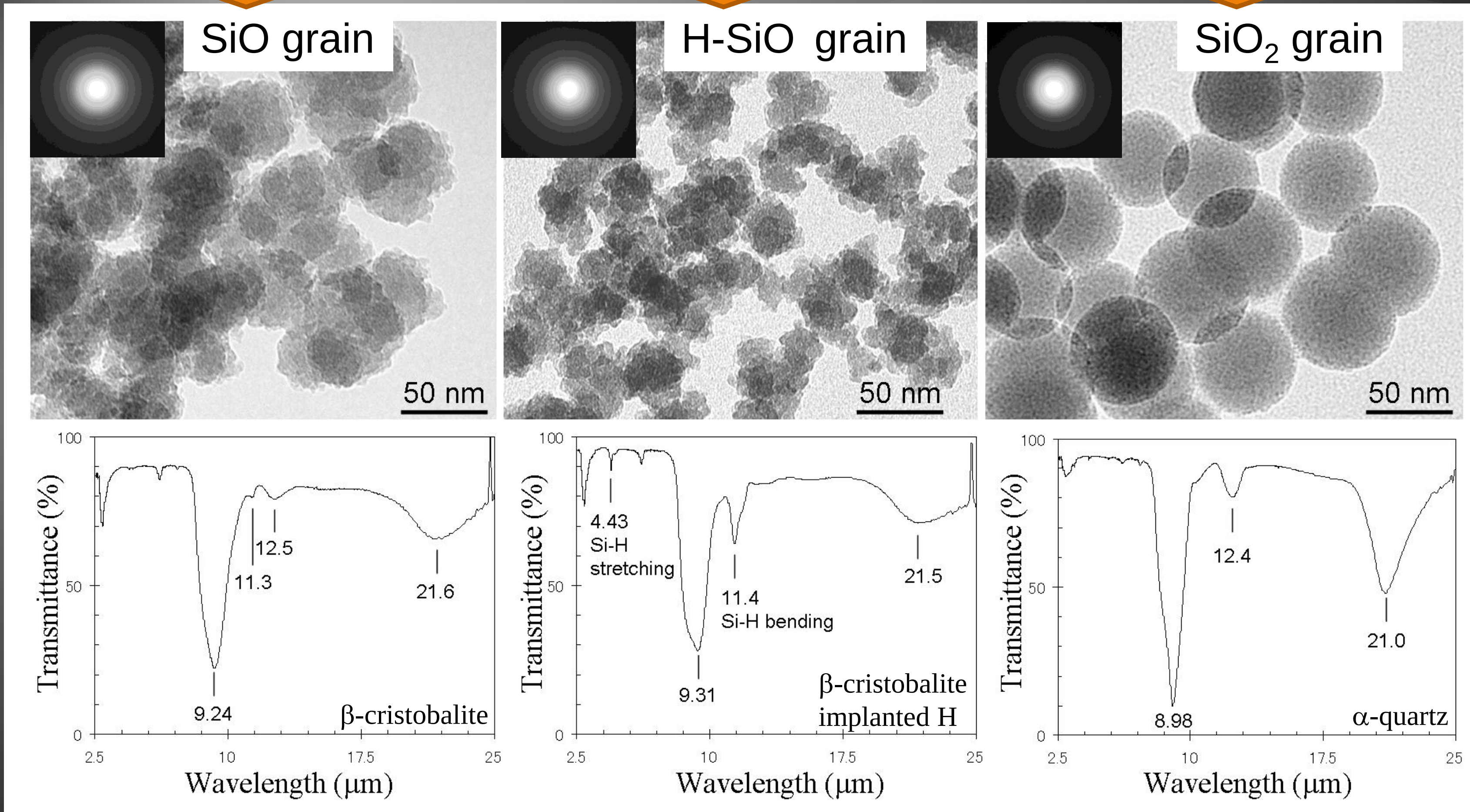


Experimental condition

Evaporant (10 mg) [K]	Gas (10kPa)
Si powder [2700]	CO gas
SiO lamp [2100]	H_2 gas
SiO lamp [2100]	$Ar + O_2$ (8 + 2 kPa) mixture gas

Results: Amorphous silicon oxide dusts

Si evaporated in CO gas   SiO evaporated in H_2 SiO evaporated in O_2+Ar (2:8)

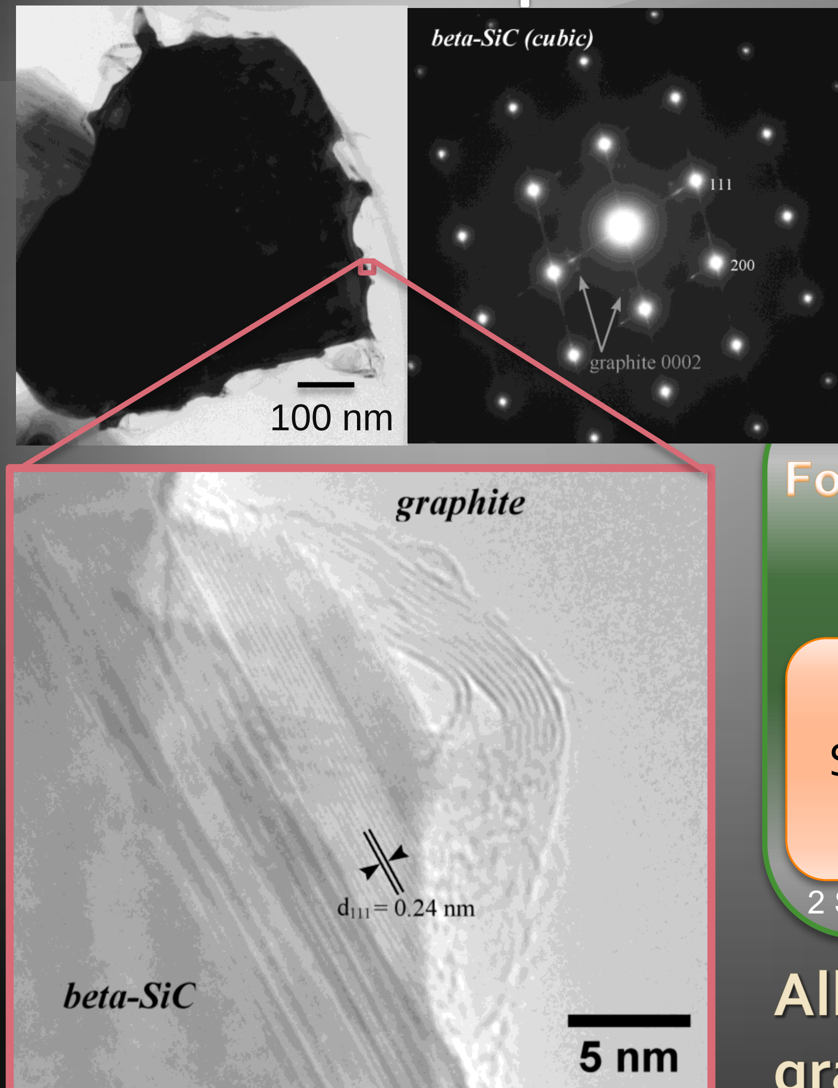


- Anneal effects of gas thermal conduction promoted coalescence growth of dust. H_2 < CO < O_2+Ar† († additionally effect of exothermic oxidation).
- Thermal stability of SiO molecule is highest stable between the species: SiO, CO, O_2, H_2 (and H_2O).

Where is carbon from a CO decomposition ?

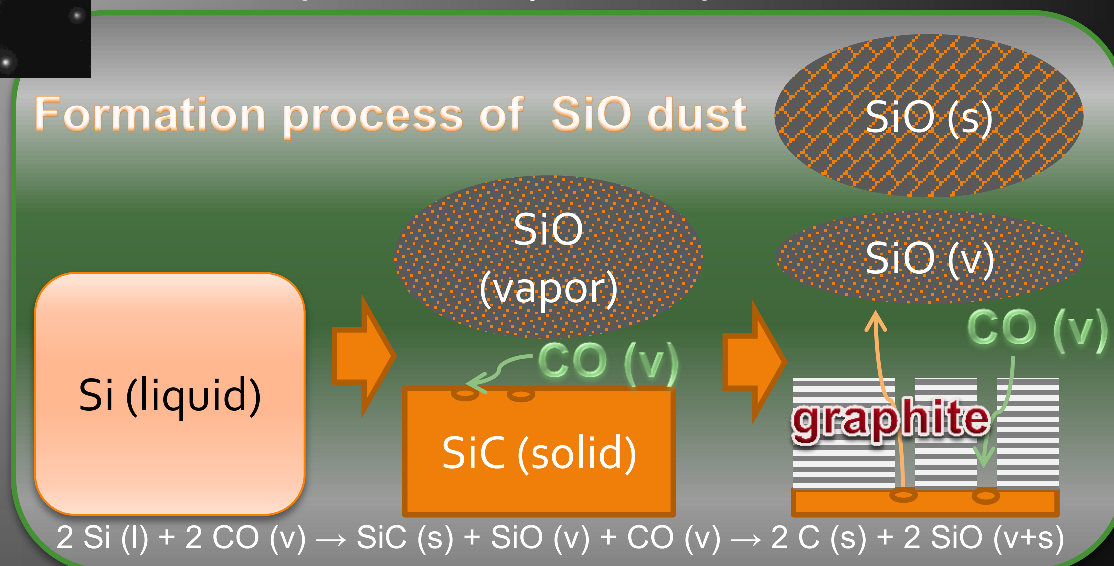
Si evaporated in CO gas

Residue on the evaporation: SiC



Residue were collected on the tungsten heater.

- ✓ Electron diffraction :
  β-SiC (zinc-blend structure)
- ✓ High-resolution electron microscopy: Graphite layer was grown on the surface of β-SiC. There is no SiO_2 layer on the β-SiC crystal.



All carbon will eventually form the graphite via SiC.

Summary of silicon oxide experiments

- **High temperature stability:**
  SiO > SiC > CO (＞H_2O)
- Silicon monoxide is carrier for oxygen under condition of abundant CO gas and/or H_2 gas.

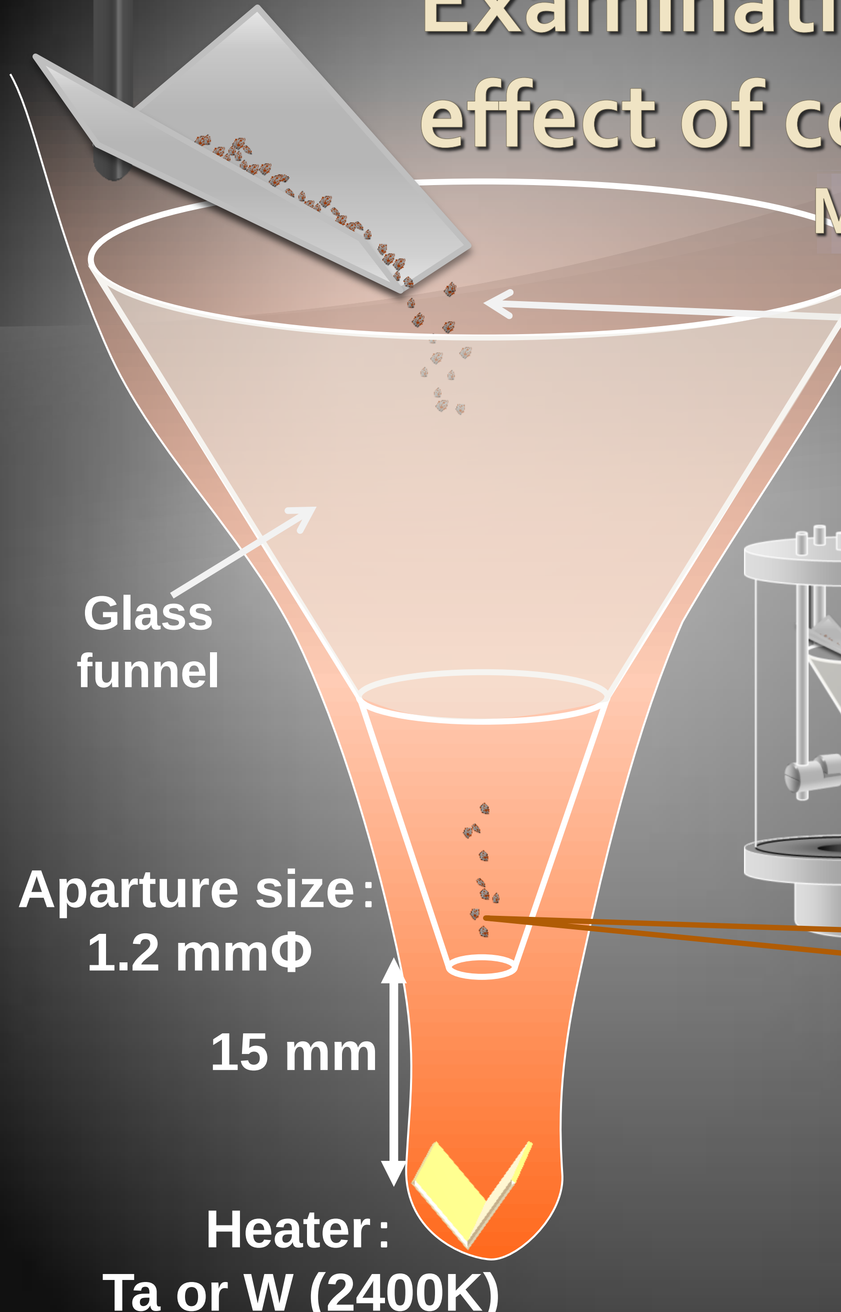
A new question:

If oxygen of SiO takes from CO of ambient around evolved star, when does it take from the stable SiO as carrier?

- The stage of formation of silicate may be chance to release an oxygen from Si-O bond.

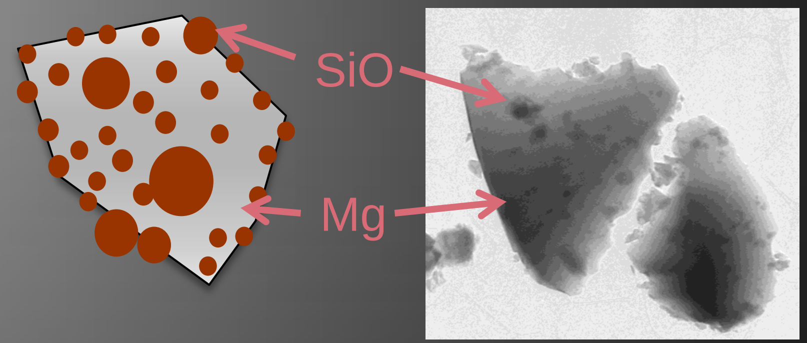
Examination of stability of SiO effect of containing Mg

Mg-SiO simultaneous evaporation



Evaporants: Mixture powder of Mg (45-75 μm) and SiO (<35 μm)

(Mg/SiO =1 atomic ratio)

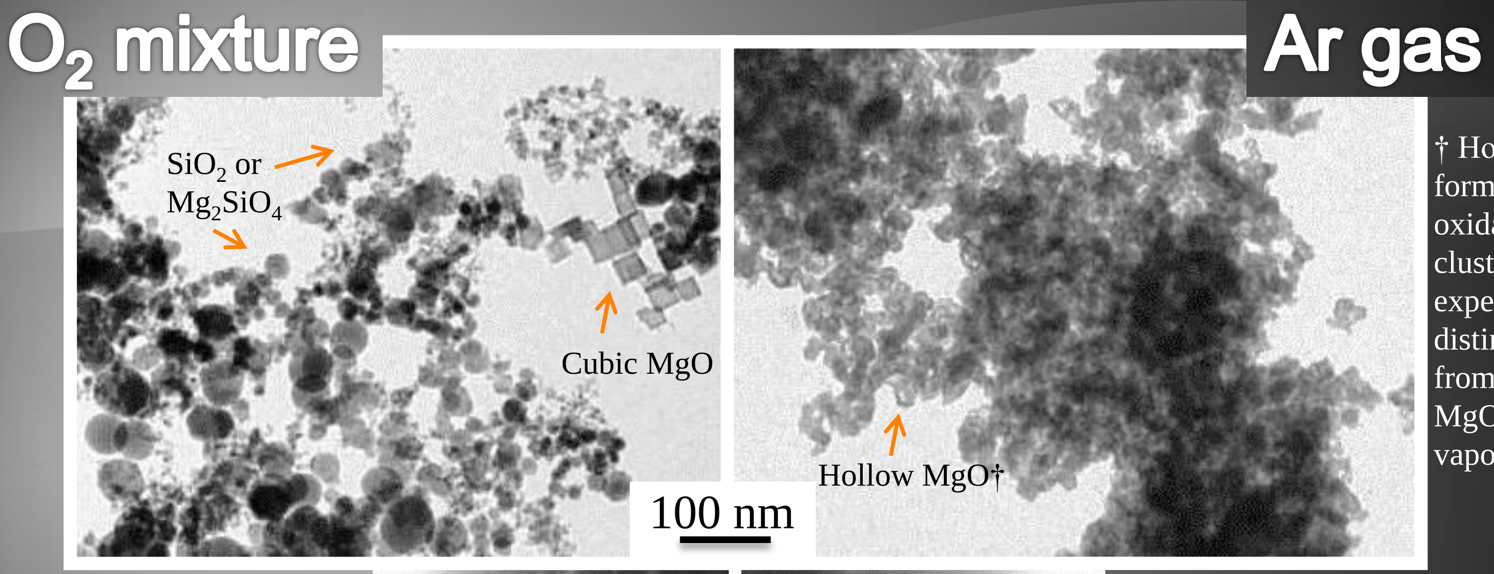


0.6 mg of the mixture powder evaporated per drop.

Ambient gas:

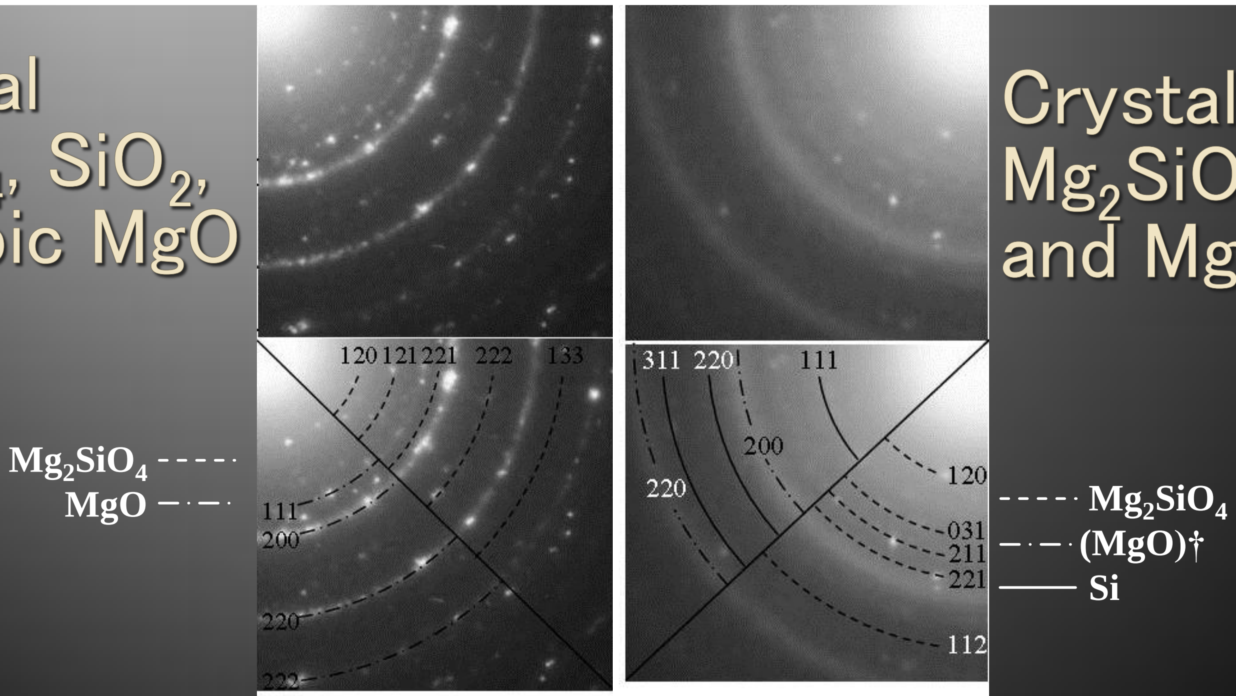
- Ar 10 kPa
- O_2 2 + Ar 8 kPa

Results of TEM analysis



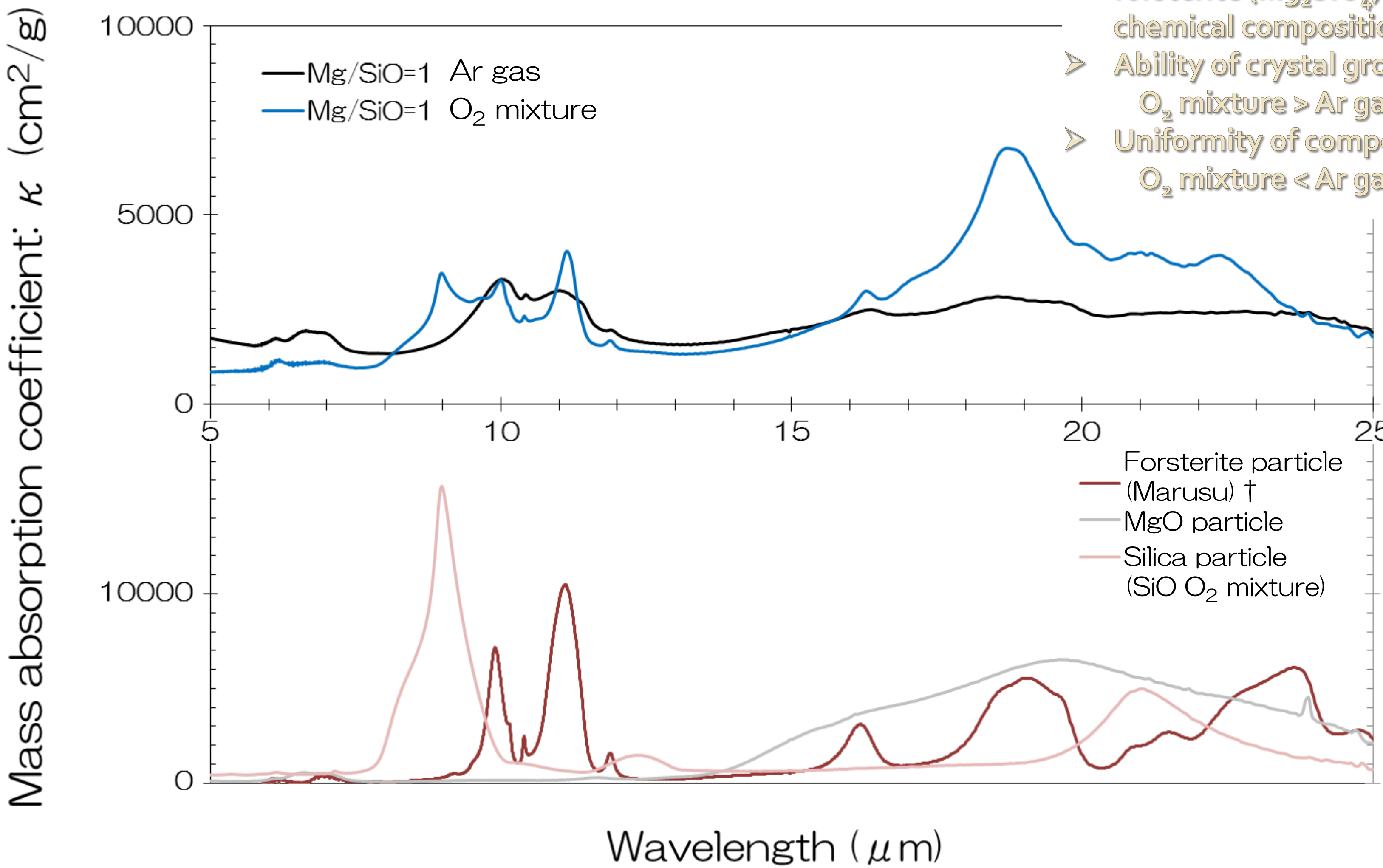
† Hollow MgO formed by air oxidation of Mg cluster after experiment is distinguishable from the cubic MgO formed by vapor condensation.

Spherical Mg_2SiO_4, SiO_2, and Cubic MgO



Crystallites of Mg_2SiO_4, Si and MgO†

Results: FT-IR analysis of Mg-silicate dusts



- Silicate tends to be forsterite (Mg_2SiO_4) chemical composition.
- Ability of crystal growth
  O_2 mixture > Ar gas
- Uniformity of compound
  O_2 mixture < Ar gas

† Koike, et al., 2010

Summary of Mg-SiO experiments

- O_2 mixture: spherical SiO_2, spherical Mg_2SiO_4 and cubic MgO
  - Exothermal effect of oxidation promoted the coalescence growth between MgO and SiO_2.
  - Conversely, in a region where lack of an exothermal effect is supplies, evolution to silicate constricted because stable oxides (MgO, SiO_2) were formed initially.
- Ar gas : Mg_2SiO_4 and Si crystallite
  - The growth of Si crystallite indicates that Mg assisted the release of oxygen from Si-O bond.
  - Composition of silicate based on forsterite (Mg_2SiO_4) was favorably produced from oxygen depletion atmosphere.

Conclusion

- **SiO is carrier for oxygen.**
  - SiO molecule is more stable than CO and H_2O at a temperature above 2200K, whereas it can be decomposition of crystallites of Si and SiO_2 below the low temperature.
- **Production of uniformly-solidified silicate** are achieved at the atmosphere of depletion of oxygen, rather than the existence of free oxygen forming saturated oxide such as MgO or SiO_2.
- **Demonstration of formation** of circumstellar silicate dust on oxidative or reductive condition requires the introduction of gas species other than oxygen controlled partial pressure.

Acknowledgment

- This work was supported by
  Grant-in-Aid for JSPS Fellows,
  Global COE Program of Kobe University and Hokkaido University "Foundation of the International Education and Research Center for Planetary Science", MEXT, Japan and
  Academic Frontier Project, MEXT, Japan.

- We thank to prof. C. Koike for valuable comments and suggestion.