GAS-PHASE CONDENSATION OF SUBMICRON-SIZED SILICATE CRYSTALS BEHIND PLANETESIMAL BOW SHOCKS

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SUMMARY: We numerically simulated the dust heating and evaporation behind a planetesimal bow shock based on the one-dimensional plane-parallel shock-wave heating model. The dust vapor rapidly cools due to the adiabatic expansion of the shocked gas. We obtained an analytic formula of the cooling timescale of the vapor. The vapor becomes highly supersaturated and fine silicate crystals with various morphologies could condense. We estimated the typical size of condensates as 1 μm or less by using the classical nucleation theory. These estimated properties of condensates match well with fine silicate crystals observed in matrix of primitive meteorites. This suggests that they have formed in the rapidly cooling silicate vapor behind the planetesimal bow shock in early solar nebula.

1 Condensation in Highly Supersaturated Silicate Vapor

There are several lines of evidences in interplanetary dust particles (IDPs) and chondritic meteorites that the dust condensed in the conditions far from equilibrium in the early solar nebula (see Fig. 1). It was suggested that these fine silicate crystals of various morphologies form by a homogeneous nucleation and successive crystal growth in a highly supersaturated silicate vapor [4, 5].

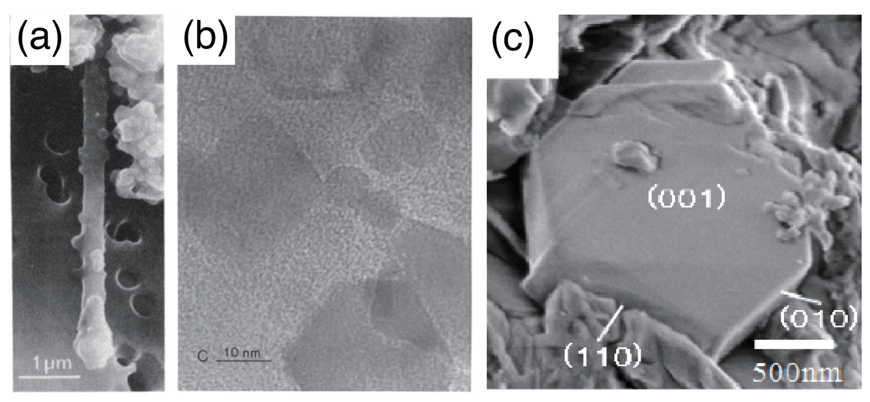

Figure 1: (a) Enstatite whisker in IDPs [1]. (b) Ultra-fine particles in matrix of Allende meteorite [2]. (c) Fine olivine crystals in matrix of Allende meteorite [3].

The morphologies depend on the condensation temperature T_c and supersaturation ratio σ. The numerical simulations of shock-wave heating showed that the planetesimal bow shock could generated highly supersaturated silicate vapor [6].

In this study, we consider the typical size and morphologies of fine silicate crystals condensed behind the planetesimal bow shock. They can be estimated from the cooling timescale and vapor density based on the classical nucleation theory [7].

2 Cooling Timescale by Adiabatic Expansion

Equation of motion for expansion:

$$\frac{dv_r}{dt} = -\frac{1}{\rho}\frac{\partial p}{\partial r}, \quad (1)$$

We adopt the one-zone approximation ($v_r \sim dR/dt$, $\partial p/\partial r \sim -p/R$), equation of state ($p = K\rho^\gamma$), and mass conservation ($\sigma = \pi R^2 \rho =$const.).

↓

Normalized equation of motion:

$$\frac{d^2\tilde{R}}{d\tilde{t}^2} = \tilde{R}^{-2\gamma+1}, \quad (2)$$

where $\tilde{R} = R/R_0$ and $\tilde{t} = t/t_{s0}$ (R_0 is the initial radius and $t_{s0} \equiv R_0/c_{s0}$ with initial sound speed c_{s0}). γ is the ratio of specific heat.

From the solution of Eq. (2) (see Fig. 2), we obtain an analytic expression of cooling rate:

$$\left(\frac{dT}{dt}\right)_{\rm HE} = -a_\gamma T_0/t_{s0}, \quad (3)$$

where $a_\gamma \sim 0.3 - 0.4$.

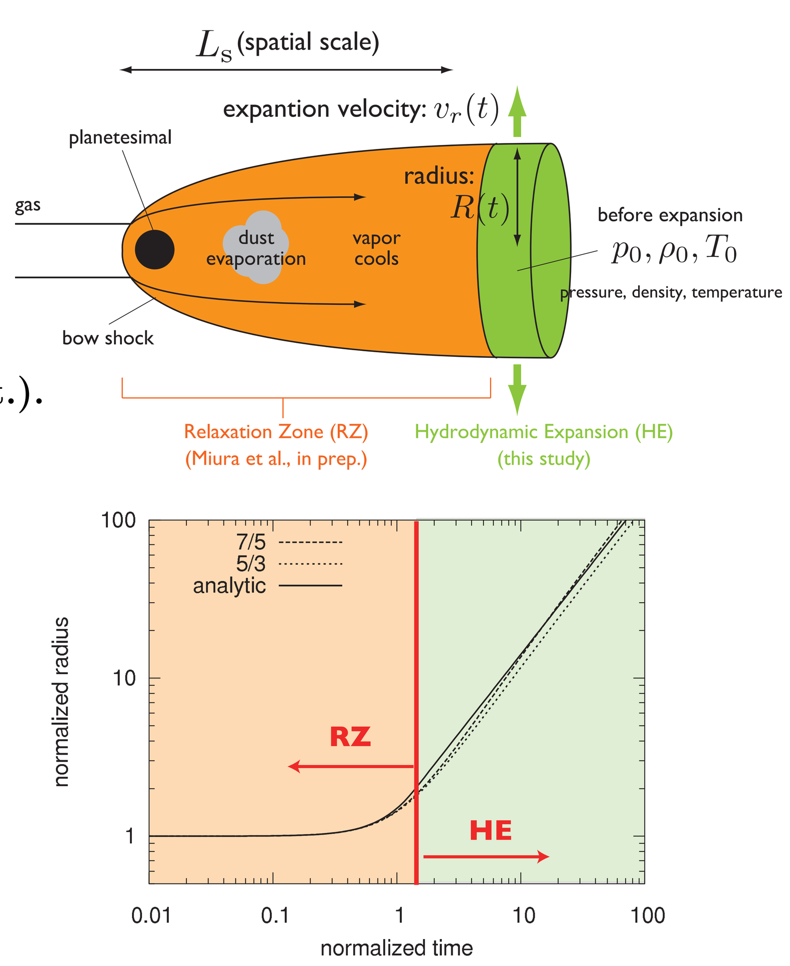

Figure 2: Schematic of planetary bow shock (top). Solution of Eq. (2) (bottom).

The timescale in which the supersaturation ratio changes:

$$\tau_{\rm sat,HE} \sim 10^{-2}(R_0^2\rho_0/p_0)^{1/2} \quad (4)$$

We consider the condensation of forsterite (Mg_2SiO_4) in H_2 atmosphere.

3 Vapor Density

Fig. 3 shows a result of numerical simulations for dust evaporation behind the shock front. The solid dust particles with radius of 0.1 μm are abruptly heated by the gas frictional heating just behind the shock front, then evaporate completely (panel a). As a result, silicate vapor forms (panel b). In this case, the vapor density is 6×10^{-11} g cm^{-3}.

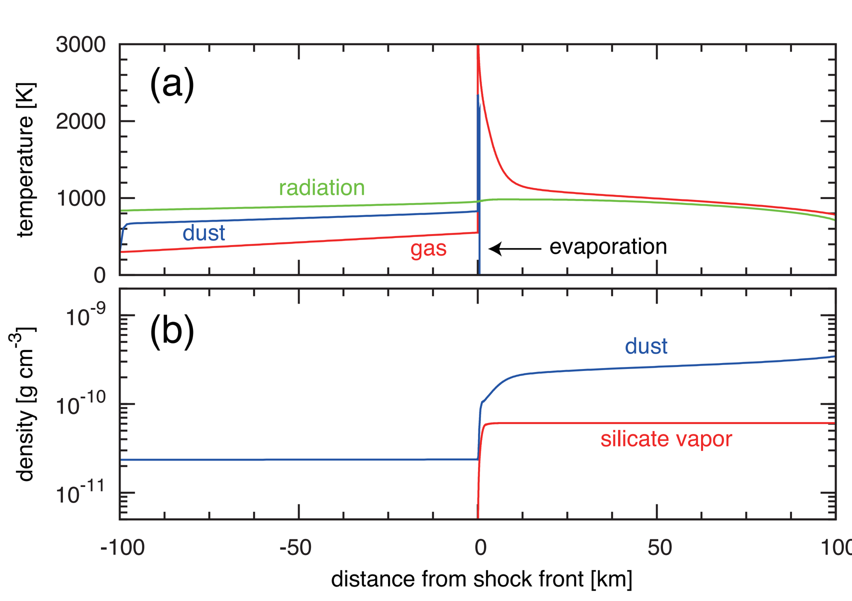

Figure 3: Numerical result of dust evaporation behind shock front (case L2n14v10c1).

4 Typical Size of Condensates

The typical size of condensates r_∞ can be estimated from the cooling timescale and the vapor density as [7] (see Fig. 4)

$$r_\infty \sim 1\ (\Lambda/10^5)\ \mu{\rm m}, \quad (5)$$

where $\Lambda \equiv \tau_{\rm sat}/\tau_{\rm coll}$ and $\tau_{\rm coll} = (4\pi r_0^2 \alpha n_0 v_{\rm th})^{-1}$ is the collision interval of vapor molecules. r_0 is the molecule radius, α is the sticking probability, n_0 is the number density of vapor molecules, and $v_{\rm th}$ is the thermal velocity. Substituting Eq. (4) into $\tau_{\rm sat}$, we obtain

$$r_\infty \sim 1 \left(\frac{R_0}{100\ {\rm km}}\right)\left(\frac{\alpha}{0.1}\right)\left(\frac{l}{1\ {\rm cm}}\right)^{-1} \mu{\rm m}, \quad (6)$$

where l is the mean free path of the vapor molecules. The calculated size of condensates for each case is listed in a table below. It is found that the typical size of condensates is ~ 1 μm or less.

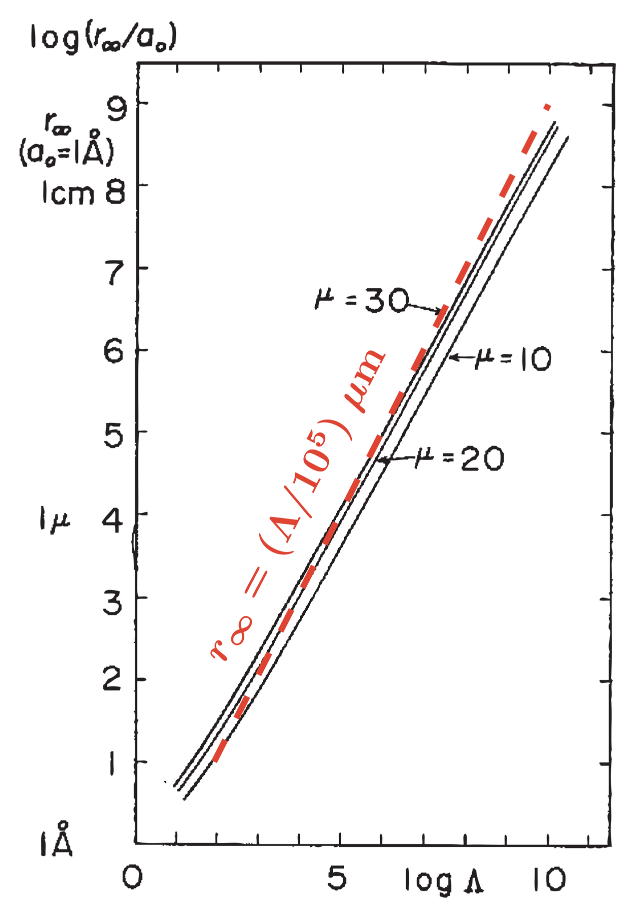

Figure 4: Typical size of condensate [7].

case	dust radius [μm]	evap. fraction	vapor density [g cm^{-3}]	mean free path [cm]	size [nm]
L2n14v10c1	0.1	0.15	6.1×10^{-11}	37	27
L2n15v08c1	10	3.1×10^{-2}	9.5×10^{-11}	23	43
L2n15v08c1	1.0	0.93	1.7×10^{-9}	1.3	770
L2n14v10c1	1.0	1.1×10^{-4}	9.0×10^{-14}	2.5×10^4	< 1 ?
L3n14v10c1	0.1	0.27	7.1×10^{-11}	31	32
L3n14v10c2	0.1	0.56	1.3×10^{-11}	170	5.9
L3n14v10c1	1.0	0.19	1.5×10^{-10}	15	67
L3n14v10c1	10	2.8×10^{-4}	2.5×10^{-13}	8.9×10^3	< 1 ?
L3n14v10c2	1.0	3.8×10^{-3}	3.2×10^{-13}	6.9×10^3	< 1 ?

5 Morphologies of Condensates

Fig. 5 shows the supercooling $\Delta T = T_e - T_c$, where T_e is the equilibrium condensation temperature and T_c is the actual condensation temperature [7]. The red, blue, and green regions indicate the experimental conditions that bulky-, platy-, columnar-, and needle-type crystals condensate, respectively [4]. It is found that platy, columnar-, and needle-types form in rapidly cooling silicate vapor (small Λ). Since our model suggests that $\Lambda < 10^5$, the bulky- and platy-types will be obtained in the case of typical silicate dusts ($\mu = 20$ [7]). The morphological property is very similar to that observed in primitive meteorites [3].

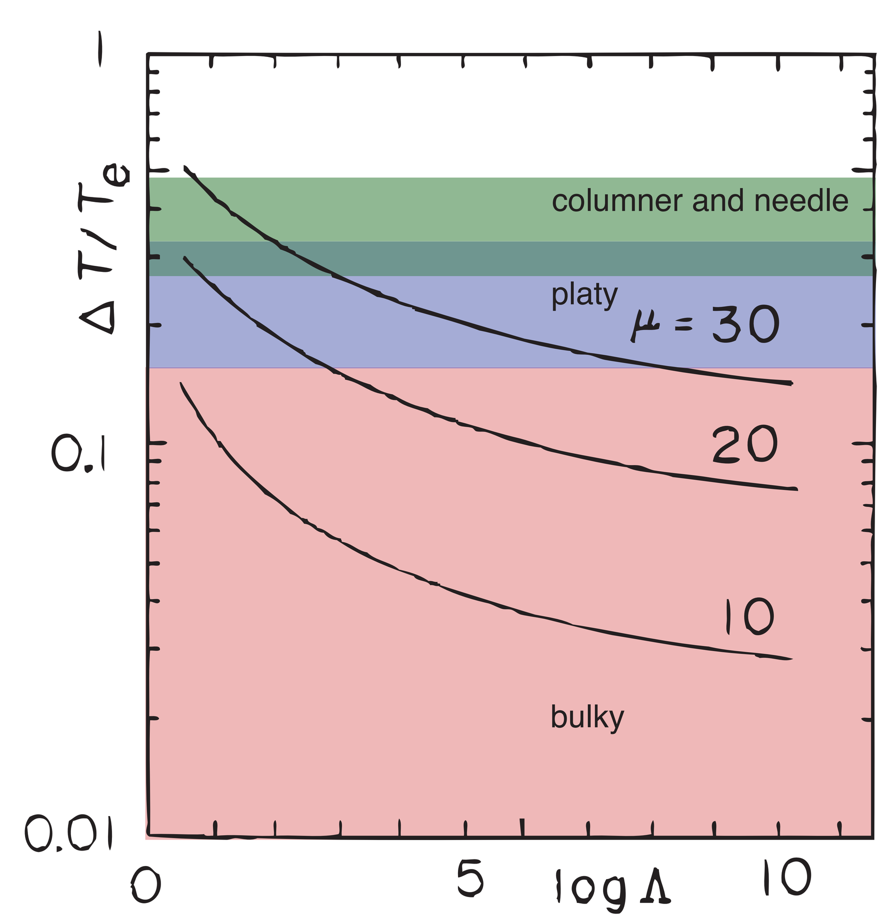

Figure 5: Supercooling at condensation in rapidly cooling vapor [7] and experimental condition in which each type of crystal condenses [4].

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