FRAGMENT-COLLISION MODEL FOR COMPOUND CHONDRULE FORMATION: ESTIMATION OF COLLISION FREQUENCY. H. Miura[1,4], S. Yasuda[2,3,4], T. Nakamoto[3], [1]*Department of Physics, Kyoto Univ., Sakyo, Kyoto 606-8502, Japan, (miurah@tap.scphys.kyoto-u.ac.jp),* [2]*Pure and Applied Sciences, Univ. of Tsukuba, Tsukuba, Ibaraki 305-8577, Japan,* [3]*Department of Earth and Planetary Sciences, Tokyo Institute of Tech., Meguro, Tokyo 152-8551, Japan,* [4]*Research Fellow of the Japan Society for the Promotion of Science.*

Introduction: Compound chondrules are composed of two or more chondrules fused together. They are rare in all chondrules ($\sim 4\%$ [e.g., 1 – 5]), but occur in many classes of chondrites, so they offer crucial information regarding the physical and chemical state of solid materials during chondrule formation. One of the models for compound chondrule formation is the random collision model, in which totally or partially molten particles collided with appropriate relative velocity [1, 3]. However, the collision frequency in the solar nebula is too small to account for the observed compound fraction because of the low density of matter in the nebula [1 – 3].

In this paper, we propose a new scenario for compound chondrule formation. The shock-wave heating model is one of the most plausible models for chondrule formation [e.g., 6]. In this model, the dust particles are exposed to high-velocity gas flow and heated by gas frictional heating. Recently, we carried out three-dimensional hydrodynamic simulations of molten dust particle exposed to the gas flow and showed that molten cm-sized dust particle is disrupted into many small pieces in a typical setting of nebula shocks [7]. These pieces have many chances of mutual collisions to form compound chondrules because the local number density of them behind the disrupted particle is enhanced. We name this scenario "fragment-collision model" and believe that it can be a strong candidate for compound chondrule formation.

The purpose of this study is to estimate the collision frequency between these pieces by using a simple formulation. In this paper, we call the disrupted dust particle as "parent" and small pieces as "ejectors." For simplicity, we assume that all ejectors have the same radius of $r_{\rm e}$.

Formulation: The number of collision per unit time (collision rate) is given by $R_{\rm coll} \sim \sigma_{\rm coll} n_{\rm e} \Delta v$, where $\sigma_{\rm coll}$ is the collisional cross-section, $n_{\rm e}$ is the number density, and Δv is the velocity dispersion of ejectors [1, 3]. The original point of our model is to estimate $n_{\rm e}$ resulting from disruption of the parent. Considering the total number of ejectors torn away from the parent during a short period of time δt, δN, and the volume of the region in which these ejectors are scattered, δV, we obtain $n_{\rm e} = \delta N/\delta V$. Assuming that all ejectors just after ejection are parting from the parent with a velocity of $\sim \Delta v$, we obtain the volume in this phase as $\delta V_0 \sim 2\pi r_{\rm p}^2 \Delta v \delta t$, where $r_{\rm p}$ is the radius of parent (see Fig. 1a). After ejection, the motions of ejectors are affected by the ambient gas flow. We simply assume that ejectors are accelerated with a constant acceleration a in the direction of the gas flow (z-axis), on the other hand, in the direction perpendicular to the gas flow (r-axis) they move with a constant velocity of $\sim \Delta v$ (see Fig. 1b). In this later phase, the region in which ejectors are scattered is getting wider steeply with time t and its volume is given by $\delta V_t \sim \pi(\Delta v t)^2 a t \delta t$. Approximating $\delta V \simeq \delta V_0 + \delta V_t$, we obtain the number density of ejectors

$$n_{\rm e} \sim R_{\rm eject}/(2\pi r_{\rm p}^2 \Delta v + \pi \Delta v^2 a t^3) \qquad (1)$$

and the collision rate

$$R_{\rm coll} \sim (2 r_{\rm e}^2 R_{\rm eject}/r_{\rm p}^2)[1 + (t/t_*)^3]^{-1}, \qquad (2)$$

where $R_{\rm eject}$ is the ejection rate defined by $R_{\rm eject} \equiv \delta N/\delta t$ and $t_* \equiv (2 r_{\rm p}^2/\Delta v a)^{1/3}$. Integrating Eq. (2) over t from 0 to ∞, we obtain the collision frequency

$$F_{\rm coll} \simeq \left(\frac{72 \rho_{\rm mat} r_{\rm e}^7 R_{\rm eject}^3}{r_{\rm p}^4 \Delta v p_{\rm fm}} \right)^{1/3}, \qquad (3)$$

where $p_{\rm fm}$ is the gas ram pressure and $\rho_{\rm mat}$ is the material density of parent and ejectors (we set $\rho_{\rm mat} = 3\,{\rm g\,cm^{-3}}$ in this paper). In Eq. (3), we substitute $a = 3 p_{\rm fm}/4 r_{\rm e} \rho_{\rm mat}$.

Ejection from Liquid Layer: In order to estimate Δv and $R_{\rm eject}$ in Eq. (3), we have to model the ejection from molten parent. Since the cm-sized parent is too large to homogenize internal temperature due to the thermal conduction, it should melt from the surface facing the gas flow [8]. Fig. 2 shows the schematic picture of this situation. For simplicity, we assume that physical properties in the liquid layer is uniform. The surface of the liquid layer is forced to move with a velocity v_θ by the tangential component of ram pressure $\sim p_{\rm fm}/2$. In contrast, there is no motion at the surface of solid core. The tangential stress of viscosity is given by $T_{r\theta} \sim \mu v_\theta / h$, where μ is the viscosity and h is the width of the liquid layer. We obtain v_θ by considering the balance between $T_{r\theta}$ and $p_{\rm fm}/2$. Assuming that Δv is the same order of magnitude of v_θ, we obtain

$$\Delta v \sim (p_{\rm fm} r_{\rm p}/2\mu)\lambda, \qquad (4)$$

where $\lambda \equiv h/r_{\rm p}$ is the normalized width of liquid layer. The total volume of liquid layer can be roughly estimated as λ times the volume of whole parent.

When the liquid layer fragments into ejectors, the total number of ejectors is $N_{\rm e} \sim \lambda (r_{\rm p}/r_{\rm e})^3$. Assuming that the fragmentation proceeds in a fluid crossing time $t_{\rm cross} \sim r_{\rm p}/v_\theta$, we obtain the ejection rate as

$$R_{\rm eject} \sim \lambda^2 (r_{\rm p}/r_{\rm e})^3 p_{\rm fm}/2\mu. \tag{5}$$

Collision Frequency: We adopt a standard set of parameters as follows: $r_{\rm p} = 1\,{\rm cm}$, $r_{\rm e} = 300\,\mu{\rm m}$, $p_{\rm fm} = 3 \times 10^4\,{\rm dyne\,cm^{-2}}$, and $\mu = 10^2$ poise. We also find that $\lambda \sim 0.05$ by considering the balance between the timescale of heat conduction and the fluid crossing time. Substituting above values, we obtain $\Delta v \sim 7.5\,{\rm cm\,s^{-1}}$ and $R_{\rm eject} \sim 1.4 \times 10^4\,{\rm s^{-1}}$. Finally, the collision frequency is

$$F_{\rm coll} \sim 0.39. \tag{6}$$

Surprisingly, above estimation is about one order of magnitude larger than the observational compound fraction. It suggests that the fragment-collision model can account for the observational fraction if only $\sim 10\%$ of all chondrules formed via the fragmentation events of cm-sized parent dust particles.

We also substitute other sets of parameters in following ranges: $r_{\rm p} = 0.5 - 2.0\,{\rm cm}$, $r_{\rm e} = 100 - 1000\,\mu{\rm m}$, $p_{\rm fm} = 10^4 - 10^5\,{\rm dyne\,cm^{-2}}$, and $\mu = 10 - 10^3$ poise and find that the collision frequency ranges about $\sim 0.1 - 1$.

Oxygen Isotopic Data: In the fragment-collision model we proposed in this paper, the constituent chondrules of compounds are likely to have similar compositions because ejectors originate the same parent. The oxygen isotopic compositions were measured for 3 sets of blurred-type compounds, 6 sets of adhering- or consorting-type compounds, and 2 sets of enveloping-type compounds [4]. It was found that in a three-isotopic diagram, all sets of blurred-, adhering-, and consorting-types fall in the typical range obtained for single chondrules from the same chondrites (CV3). These results suggest that the two constituent chondrules of these compounds originated from the same dust reservoirs as those single chondrules. These observations are consistent with our new model for compound chondrule formation.

In contrast, in one set of enveloping-type, the oxygen isotopic compositions differ between two constituent chondrules. This result might suggest that this enveloping-type compound has not formed by our new model but the relict grain model as suggested by [2, 9].

Summary: We proposed a new scenario for compound chondrule formation named as "fragment-collision model," in the framework of the shock-wave heating model. We modeled the disruption of molten cm-sized dust particle exposed to high-velocity gas flow in order to estimate the efficiency of mutual collisions between small fragments. The predicted collision frequency was $\sim 0.1 - 1$, which is about one order of magnitude larger than the observational compound fraction. We concluded that this new model can account for compound chondrule formation.

Refs.: [1] Gooding & Keil (1981) *Meteoritics* **16,** 17-43. [2] Wasson et al. (1995) *GCA* **59,** 1847-1869. [3] Sekiya & Nakamura (1996) *Proc. NIPR Symp. Antarct. Meteorites* **9,** 208-217. [4] Akaki & Nakamura (2005) *GCA* **69,** 2907-2929. [5] Ciesla et al. (2004) *MAPS* **39,** 531-544. [6] Connolly & Love (1998) *Science* **280,** 62-67. [7] Miura & Nakamoto (2007) *Icarus* **188,** 246-265. [8] Yasuda & Nakamoto (2005) *LPSC XXXI,* #1252 (abstract). [9] Wasson (1993) *Meteoritics* **28,** 14-28.

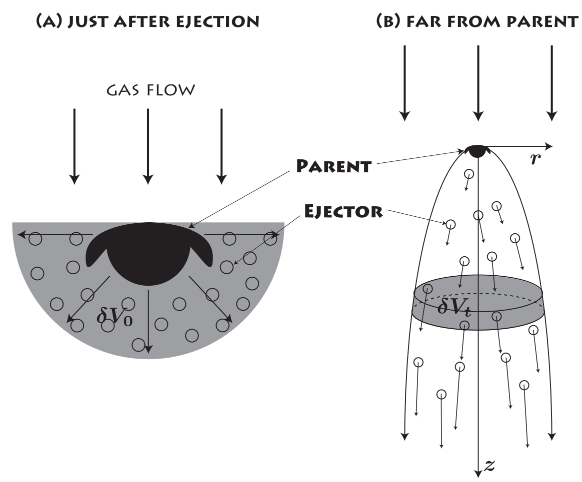

Figure 1: Schematic picture of disruption of molten parent dust particle exposed to high-velocity gas flow. When the gas ram pressure is too strong for the molten parent to keep its shape, many small ejectors are dispersed behind the parent. These ejectors have many chances of mutual collisions to form compound chondrules because the local number density of them behind the parent is enhanced.

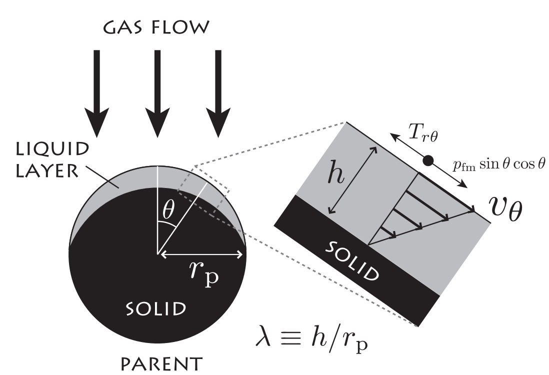

Figure 2: Schematic picture of liquid layer formed at the surface of parent particle.