FRAGMENT-COLLISION MODEL FOR COMPOUND CHONDRULE FORMATION: SIZE RATIO OF SECONDARY TO PRIMARY. H. Miura[1], S. Yasuda[2,3,4], T. Nakamoto[3], [1]*Graduate School of Science, Tohoku Univ., Aoba, Sendai 984-8578, Japan, (miurah@ganko.tohoku.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. Recently, we propose a new scenario for compound chondrule formation in the framework of the shock-wave heating scenario, "fragment-collision model," which can account for the observed fraction of compound chondrules [6]. In this model, a cm-sized silicate dust particle (parent) are heated and melted by the gas frictional heating, then the molten parent is disrupted due to the strong gas ram pressure. Many small fragments (ejectors) are extracted from the molten parent particles and accelerated by the ambient gas flow (see Fig. 1). The mutual collisions between ejectors will occur and cause the compound chondrule formation.

In this model, it is suggested that the mutual collisions are more likely to occur on a pair of different-sized ejectors than a similar-sized pair because the acceleration of ejectors depends on their sizes. The difference of the acceleration results in the large relative velocity between ejectors, so the collisions are encouraged. In observations, a compound chondrule with the different-sized pair is frequently observed more than the similar-sized pair. The mean value of the size ratios of secondaries to primaries is about 0.3 [2]. If the fragment-collision model accounts for the observed size ratio of compound chondrules, it is a strong evidence that these compound chondrules have been formed by the fragment-collision. However, in our previous work, only the collision probability between two same-sized ejectors was derived.

The purpose of this study is to obtain the formation probability of compound chondrules with different-sized pair based on the formulation of the fragment-collision model [6].

Model: We consider that there are ejectors of two different sizes; the radii of large ejectors are r_1 and small ones are r_2. We call the large ejectors "primaries" and smaller ones "secondaries." The collision rate between two different-sized ejectors, $R'_{\rm coll}$, is defined as *the number of collision with primaries experienced by a secondary per unit time* in this study. The collision rate is given by

$$R'_{\rm coll}(z) = n_1(z)\sigma'_{\rm coll}v_{\rm rel}(z), \qquad (1)$$

where $n_1(z)$ and $v_{\rm rel}(z)$ are the number density of primaries and the relative velocity between primary and secondary at the position z from the parent, respectively (see Fig. 1). The collisional cross-section $\sigma'_{\rm coll}$ is $\pi(r_1 + r_2)^2$. The number density of primary is given by Eq. (2) in [6][1]. We set $v_{\rm rel}(z)$ as

$$v_{\rm rel}(z) = \Delta v + |v_1(z) - v_2(z)|, \qquad (2)$$

where Δv is the velocity dispersion between ejectors [6]. The velocities of primary and secondary parting from the parent, $v_1(z)$ and $v_2(z)$, are given by Eq. (33) in [6]. In order to obtain the probability of compound chondrule formation, $P'_{\rm comp}$, we can integrate $R'_{\rm coll}(z)$ over z as

$$P'_{\rm comp} = \int_{z_{\rm cool}}^{z_{\rm dest}} R'_{\rm coll}(z)\frac{dz}{v_2(z)}, \qquad (3)$$

where $z_{\rm cool}$ is the distance from the parent at which the primary cools due to the radiative cooling, and $z_{\rm dest}$ is the distance beyond which the relative velocity $v_{\rm rel}(z)$ exceeds the critical destruction velocity $v_{\rm dest}$, which indicates the critical velocity above which the two colliding ejectors will be disrupted [6]. It should be noted that $dz/v_2(z)$ is the infinitesimal period in which the secondary travels the distance of dz. We obtain $z_{\rm cool} \simeq 750\,{\rm cm}$ if considering that the primary with radius of $r_1 = 500\,\mu{\rm m}$ cools by $100\,{\rm K}$ [6]. The distance $z_{\rm dest}$ depends on $v_{\rm dest}$. We consider three cases; $v_{\rm dest} = 10^3$, 10^4, and $10^5\,{\rm cm\,s^{-1}}$, respectively. For comparison, we also calculate a case of $v_{\rm dest} = \infty$, which corresponds to a case that the collisional destruction does not occur (no destruction).

Results: Fig. 2 shows the probability of compound chondrule formation $P'_{\rm comp}$ as a function of the size ratio of secondary to primary r_2/r_1. We set the gas ram pressure $p_{\rm fm} = 3 \times 10^4\,{\rm dyn\,cm^{-2}}$, the viscosity of molten dust particle $\mu = 10^2\,{\rm g\,cm^{-1}\,s^{-1}}$, and the radius of primary $r_1 = 500\,\mu{\rm m}$. In this case, the velocity dispersion is $\Delta v \sim 4.0\,{\rm cm\,s^{-1}}$ [6]. The solid curve corresponds to the case of no destruction ($v_{\rm dest} = \infty$), and other curves are cases for $v_{\rm dest} = 10^3$, 10^4, and $10^5\,{\rm cm\,s^{-1}}$, respectively, as labeled in the figure. The curve for $v_{\rm dest} = 10^5\,{\rm cm\,s^{-1}}$ is almost the same as the case of no destruction. It suggests that almost of collisions occur with the relative velocity less than $10^5\,{\rm cm\,s^{-1}}$. In the case of $v_{\rm dest} = 10^4\,{\rm cm\,s^{-1}}$, the probability is significantly

[1]Notice that the distance from the parent, z, relates with the time after extraction of primary and secondary, t_1 and t_2, by Eq. (31) in [6].

smaller than the case of no destruction. The probability has a peak at $r_2/r_1 \simeq 0.66$ and becomes zero at $r_2/r_1 \lesssim 0.36$. In the case of $v_{\rm dest} = 10^3\,{\rm cm\,s^{-1}}$, the probability has a peak at $r_2/r_1 \simeq 0.94$ and becomes zero at $r_2/r_1 \lesssim 0.88$. Therefore, the probability for compound chondrule formation $P'_{\rm comp}$ strongly depends on the critical destruction velocity $v_{\rm dest}$.

On the other hand, we can see that the mutual collisions between different-sized ejectors are strongly encouraged more than that between same-sized ones. In every cases, the probability for compound chondrule formation for $r_2/r_1 = 1$ is very small ($P'_{\rm comp} = 3.6 \times 10^{-3}$). In contrast, the peak values of the probability are 0.40, 2.3, and 4.5 for $v_{\rm dest} = 10^3$, 10^4, and $10^5\,{\rm cm\,s^{-1}}$, respectively. The probability of compound chondrule formation can be enhanced by a factor of $100 - 1000$ by considering the collisions between different-sized ejectors.

Discussion: It was mentioned that as chondrules cool they can survive collisions with one another at velocity up to $10^4\,{\rm cm\,s^{-1}}$ due to viscous dissipation in the melt [5]. If we adopt $v_{\rm dest} = 10^4\,{\rm cm\,s^{-1}}$ as a typical case, the probability for compound chondrule formation $P'_{\rm comp}$ has a peak at $r_2/r_1 \simeq 0.66$ (see Fig. 2). Assuming that $P'_{\rm comp}$ reflects the distribution of size ratios of secondaries to primaries, the estimated mean values will be ~ 0.66. In contrast, the observed mean values of the size ratio is ~ 0.3 [2]. There are a difference of about a factor of 2 between our model prediction and the observations. In order to reconcile the difference, it might be important to take into account other effects, e.g., the shadow effect (the gas flow is blocked by the parent and/or numerous numbers of ejectors), size distribution of ejectors (because we consider only two sizes of ejectors in this study), and so forth. These issues will be investigated in the forthcoming paper.

Summary: We calculated the formation probability of compound chondrules with two different-sized ejectors as a function of the size ratio of secondary to primary. We found that the probability can be enhanced by a factor of $100-1000$ by considering the mutual collision between two different-sized ejectors. In addition, it was found that the probability strongly depends on the critical destruction velocity $v_{\rm dest}$, which indicates the critical velocity above which the two colliding ejectors will be disrupted. When we adopted $v_{\rm dest} = 10^4\,{\rm cm\,s^{-1}}$ as suggested by [5], the estimated mean values of the size ratio of secondary to primary is ~ 0.66. In contrast, since the observed mean value of the size ratio is ~ 0.3, there are a difference of about a factor of 2 between our model prediction and the observations. In order to reconcile the difference, it might be important to take into account other effects, e.g., the shadow effect (the gas flow is blocked by the parent and/or numerous numbers of ejectors), and/or the size distribution of ejectors (because we consider only two sizes of ejectors in this study).

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] Miura et al., *Icarus,* in press (arXiv:0711.0427).

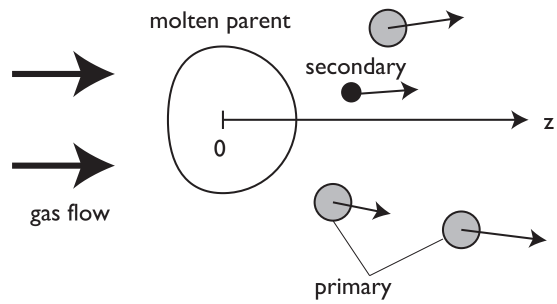

Figure 1: Schematic picture of collision between the small secondary ejector with radius r_2 (black circle) and large primary ejector with radius r_1 (gray circle) extracted from the cm-sized molten parent dust particle (white circle). The secondary and primary are accelerated by the ambient gas flow. The acceleration of primary is different from that of secondary, so the relative velocity between them will be generated and it encourages the mutual collisions.

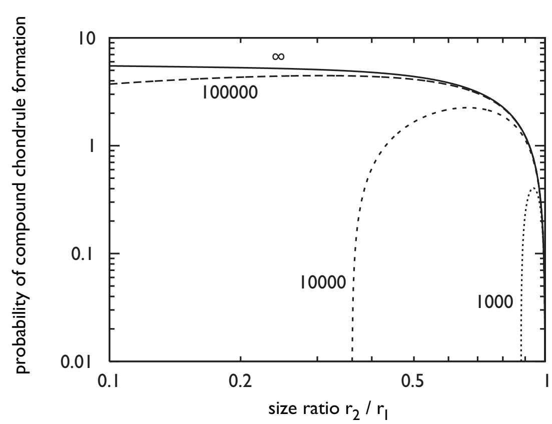

Figure 2: Probability for compound chondrule formation by two different-sized ejectors with radius r_1 (larger one, primary) and r_2 (smaller one, secondary) as a function of the size ratio r_2/r_1. We set $r_1 = 500\,\mu{\rm m}$. The critical destruction velocity $v_{\rm dest}$ is chosen as $v_{\rm dest} = 10^3$, 10^4, and $10^5\,{\rm cm\,s^{-1}}$ as labeled in this figure. The case of $v_{\rm cr} = \infty$ (no destruction) is displayed for comparison.