COLLISIONAL DESTRUCTION OF CHONDRULES IN SHOCK WAVES AND INFERRED DUST TO GAS MASS RATIO. T. Nakamoto[1] and H. Miura[2]; [1]Center for Computational Physics, University of Tsukuba, Tsukuba 305-8577, Japan, nakamoto@rccp.tsukuba.ac.jp; [2]Pure and Applied Sciences, University of Tsukuba, Tsukuba 305-8571, Japan, miurah@rccp.tsukuba.ac.jp.

Introduction: Chondrules are thought to have formed through some heating events in the early solar nebula. Although no heating mechanism proposed to date has been widely accepted, one of the most plausible models is shock wave heating [1]. For example, the shock-wave heating model can explain the heating and melting of chondrules with appropriate shock waves [2-4], the stability of liquid droplets in the solar nebula [5], the cooling rate of the chondrules inferred from laboratory experiments [2-4], and the maximum size of chondrules [6].

Basic mechanism of the shock wave heating is simple. When a shock wave is generated in the solar nebula, which is a mixture of gas and dust particles, gas is decelerated by the gas pressure while the dust particles tend to keep their initial velocity. Because of this different dynamical behavior behind the shock wave front, a relative velocity between gas and the dust particle is generated. And dust particles are decelerated by the gas drag force caused by the relative velocity with the gas, and are heated by the drag heating.

The drag force acting on a dust particle depends on the relative velocity with the gas (V_{rel}), the gas density (ρ_{gas}), the inner density of dust material (ρ_{mat}), and the radius of the dust particle (r): a time scale with which the relative velocity V_{rel} decreases to a half of the initial value, the stopping time t_s, is given by $t_s = \rho_{mat}\, r / (\rho_{gas} V_{rel})$. It is seen that smaller particles stop earlier than larger particles after passing through the shock wave front. This means that relative velocities among dust particles with different sizes are also raised behind the shock wave front. Then it is expected that mutual collisions among dust particles occur. The collision velocity could be 1 km s^{-1} or more, depending on the shock velocity and the dust particle sizes, which implies that collisional destruction of dust particles, i.e., destruction of chondrules in postshock region may occur as well. If the collisional destruction takes place significantly and all the chondrules are destructed completely, we may not expect that the shock-wave heating is responsible for the chondrule formation. Thus, the collisional destruction of chondrules in the postshock region should be examined in order to see if the shock-wave heating model is still plausible or not.

Here, we investigate the collisional destruction of dust particles in the postshock region along the shock-wave heating chondrule formation model. Taking into account the motions of many dust particles with different sizes and mutual collisions among them, we evaluate the collisional destruction rate for a dust particle passing through the shock wave. Since the collision rate is proportional to the dust mass concentration, we can also derive a condition for the dust to gas mass ratio before entering the shock wave that can reconcile the chondrule size distribution in ordinary chondrites.

Model: The shock-wave heating model by [2,7] is used to calculate the motion of dust particles with various sizes. In the model, the flow in the shock wave is assumed to be steady and plane-parallel for simplicity. The gas flow is calculated following hydrodynamical equations including energy gain and loss for the gas and the non-equilibrium chemical reactions among gas species. Motions of dust particles are calculated simultaneously with the gas flow, along with the thermodynamics calculations of those particles. From these calculations, we can obtain the velocity, the temperature, and the spatial number density of dust particles as a function of the dust radius and the place. Also, we can evaluate the relative velocity of a dust particle with respect to other dust particles and the number of collisions at each place. Since the collision velocity can be evaluated as well, we can evaluate whether of not the target particle is destructed by the collision using a criterion described below. By counting the number of destructive collisions for a certain dust particle, we can evaluate the destruction rate. And using the destruction rate, we can infer if the dust particle with the certain size can survive the shock wave and form a chondrule.

Laboratory experiments of the collisional destruction of dust particles [e.g., 8] show that dust particles are expected to be disrupted when the impact meets a certain condition. Here, we adopt a simple criterion given by $\varepsilon M_t < f\, m_p\, v_{rel}^2/2$, where $\varepsilon = 3 \times 10^6$ erg g^{-1} [8], M_t is the mass of the target particle, m_p is the mass of the projectile, v_{rel} is the relative velocity between two dust particles, and f is the efficiency assumed to be $f = 0.3$ in this study.

Size distribution of dust particles before entering the shock wave influences the final result significantly, because the number of collisions is mainly determined by the number of particles of each size. An analysis for the origin of chondrule size distribution [9] suggests that the size distribution of chondrules almost directly reflects the size distribution of precursor particles. Thus, following the chondrule size distribution, the size distribution as $n(r) = C \exp[-(\log_{10} r - \log_{10} \langle r \rangle)^2/D^2]$ is assumed here for the precursor particles, where C is a coefficient proportional to the dust mass concentration, r is the rudius measured in μm, $\langle r \rangle = 250$ μm is the mean radius, and $D^2 = (\log_{10} 2)^2$ is the square of the dispersion. The initial dust to gas mass ratio is assumed to be 0.001, 0.01, and 0.1, in this study. Note that the solar abundance value of the dust/gas mass ratio is about 0.01.

Results: Fig. 1 shows the calculated destruction rates as a function of the target particle radius for a case with the preshock gas number density $n_0 = 10^{14}$ cm^{-3} and the shock velocity $v_s = 8$ km s^{-1}. Three curves represent destruction rates for different initial dust/gas mass ratios. The destruction rate is proportional to the initial dust/gas mass ratio: it is high for a high initial dust/gas mass ratio case, because the number of collisions is proportional to the total mass of dust. When a target dust particle is larger than a critical radius, the destruction rate of the particle exceeds unity, implying that the dust particle is expected to be destructed in the shock wave: the critical radii for each initial dust/gas mass ratio, which are displayed by arrows in Fig. 1, are 330 μm (for $(\text{dust/gas})_{\text{init}} = 0.1$), 750 μm (0.01), and 2 mm (0.001), respectively. It seems difficult to reproduce chondrules seen in ordinary chondrites with initial dust/gas mass ratio much higher than 0.01, because the critical radius becomes smaller than the mean radius of observed chondrules. It may be worth noting that simulated thermal histories of dust particles indicate that most of the particles in the shock wave are heated enough and can form chondrules.

Fig. 2. displays the destruction rates with the shock wave $n_0 = 10^{11}$ cm^{-3} and $v_s = 40$ km s^{-1}. Most of the dust particles are heated enough and form chondrules, if the collisional destruction is not taken into consideration. However, particles larger than critical radii are expected to be destructed in the shock wave. The critical radii in this case are 130 μm (for $(\text{dust/gas})_{\text{init}} = 0.1$), 310 μm (0.01), and 730 μm (0.001), respectively. Again, it seems difficult for shock waves with higher initial dust/gas mass ratio to form chondrules as large as chondrules seen in ordinary chondrites. Therefore, it is inferred that the dust/gas mass ratio before entering the shock waves should be of the order of or less than 0.01 in order to reproduce the chondrule size distribution in ordinary chondrites.

Summary: The shock-wave heating model for chondrule formation naturally implies that the relative motions and mutual collisions among dust particles (chondrules) in the postshock region are present. We examined the collisional destruction of chondrules in the shock wave and found that dust particles larger than the critical radius are destructed in the shock wave. The critical radius depends on the initial dust/gas mass ratio. The initial dust/gas mass ratio should be of the order of or less than 0.01, otherwise, the chondrule size distribution in ordinary chondrites cannot be reconciled.

References: [1] Jones R. H. et al. (2000) *Protostars and Planets IV*, 927-962. [2] Iida A. et al. (2001) *Icarus 153*, 430-450. [3] Desch S. J. and Connolly H. C. Jr. (2002) *Meteoritics & Planet. Sci. 37*, 183-207. [4] Ciesla F. J. and Hood L. L. (2002) *Icarus 158*, 281-293. [5] Miura H. et al. (2002) *Icarus 160,* 258-270. [6] Susa H. and Nakamoto T. (2002) *ApJL 564*, L57-L60. [7] Miura H. and Nakamoto T. submitted to *Icarus*. [8] Takagi Y. et al. (1984) *Icarus 59*, 462-477. [9] Miura H. and Nakamoto. T. (2004) abstract in *LPSC 35*.

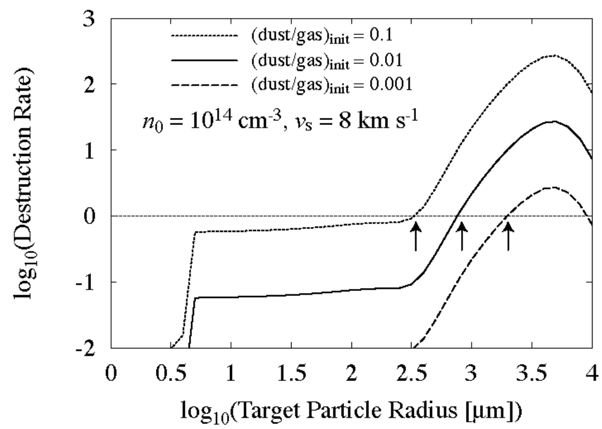

Fig.1. Collisional destruction rates as a function of target particle radius for three initial dust/gas mass ratio cases. The preshock gas number density is 10^{14} cm^{-3} and the shock velocity is 8 km s^{-1}. The critical radii above which dust particles are expected to be destructed by collision (displayed by arrows) are 330 μm ($(\text{dust/gas})_{\text{init}} = 0.1$), 750 μm (0.01), and 2 mm (0.001), respectively.

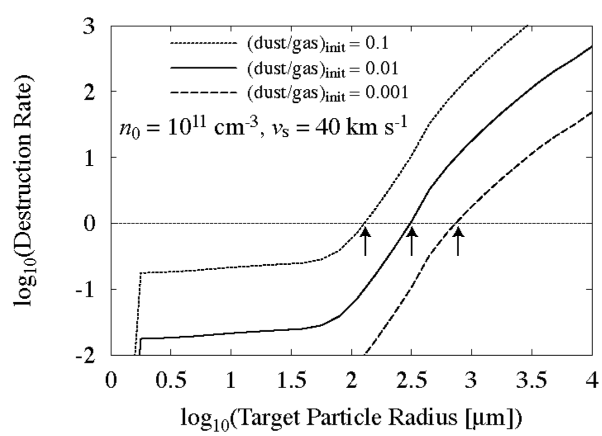

Fig. 2. Collisional destruction rates for a shock wave whose preshock gas number density is 10^{11} cm^{-3} and shock velocity is 40 km s^{-1}. Critical radii are 130 μm ($(\text{dust/gas})_{\text{init}} = 0.1$), 310 μm (0.01), and 730 μm (0.001), respectively.