A SHOCK-WAVE HEATING MODEL FOR CHONDRULE FORMATION: MECHANISM TO DETERMINE MINIMUM SIZE OF CHONDRULES.
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Introduction: Chondrules have a typical size distribution between about a few tens μm to a few mm [e.g., 1]. This size distribution should have a close relation to the chondrule formation mechanism. We explore the relation in this study based on a shock-wave heating chondrule formation model. The shock-wave heating model is one of the most popular models for chondrule formation. Many authors argue that the precursor dust particles can melt, solidify, and form chondrules by this mechanism. Here, we report that chondrules formed through this mechanism have minimum size below which no chondrule exists. Our computational experiments indicate that this minimum size is about 1 – 10 μm. This result agrees with the size distribution of chondrules in CO chondrites [1].

Model: We assume that shock waves are generated in the solar nebula and they are steady and plane-parallel. The shock velocity v_s and the number density of nebular gas n_{pre} are principal parameters in this study. We calculate the postshock structure taking into account nonequilibrium chemical reactions and thermodynamical evolutions of precursor grain particles based on the algorithm of [2]. This procedure is very similar to that adopted in [3]. We additionally include the shrinkage of precursor particle radius and the latent heat cooling caused by the evaporation. We assume that the precursor particles are composed of forsterite in order to estimate the evaporation rate J_{evap} with the kinetic theory of gaseous molecules. It is given by [4]

$$J_{evap} = 3.2\times10^{-4}\left(\frac{P_H}{10^2\,\text{dyne cm}^{-2}}\right)^{1/2} \times\left(\frac{K_{eq}}{1.82\times10^{-9}}\right)^{1/6}\left(\frac{T_{gr}}{2171\text{ K}}\right)^{-1/2}\text{g cm}^{-2}\text{ s}^{-1}, \quad (1)$$

where P_H is the partial pressure of hydrogen molecules and T_{gr} is the temperature of precursor particle. The equilibrium reaction constant K_{eq} is given by

$$K_{eq} = 1.85\times10^{29}\exp\left(-1.9\times10^5/T_{gr}\right). \quad (2)$$

The shrinkage rate of the precursor radius accompanied with the evaporation $\dot{a}_{gr}$ can be calculated by

$$\dot{a}_{gr} = -J_{evap}/\rho_{gr}, \quad (3)$$

where ρ_{gr} is the density of precursor particles.

Results and Discussion:

Temperature evolution: Figure 1 shows the temperature evolution of the gas and dust particles with two different initial radii a_0 = 1 μm (left panel) and a_0 = 1 mm (right panel) in the postshock region against the distance from shock front x. The shock velocity and the preshock gas density of this case is v_s = 15 km s^{-1} and $n_{pre} = 10^{13}$ cm^{-3}, respectively. The dust particle with a_0 = 1 μm (left panel) melts completely due to the drag heating. After the melting, this particle cools due to the radiative cooling, solidifies, and forms a chondrule. However, the postshock hot gas keeps the temperature of the dust particle very high (> 2000 K), so the dust particle continues to shrink by the evaporation and eventually vanishes at $x \sim 19$ km. Thus, we cannot observe this particle as a chondrule today. On the contrary, the precursor particle with a_0 = 1 mm (right panel) becomes a chondrule without being evaporated completely.

Final size of particles: We calculate final sizes of chondrules which have survived the postshock hot gas for a wide variety of shock parameters, v_s = 3 – 70 km s^{-1} and $n_{pre} = 10^{10} - 10^{15}$ cm^{-3}. In Figure 2, the chondrule radius a_{chond} is shown against the shock velocity. The preshock density for these cases is $n_{pre} = 10^{13}$ cm^{-3}. Symbols on the left border (at v_s = 5 km s^{-1}) show the initial sizes of precursor particles in Fig. 2. It is seen that the final sizes of many of the survived particles are about 1 – 10 μm or larger. Few exceptions are those whose final sizes are less than 1 μm and have initial sizes larger than 1 mm. They have evaporated to 1/100 or less in their sizes. These results, along with other n_{pre} cases, suggest that the minimum size of chondrules is about 1 – 10 μm. This minimum size is consistent with the size distribution of chondrules in CO chondrites [1].

Estimation of minimum size: We estimate the minimum chondrule radius presented by three dashed lines in Fig. 2 using a simple physical consideration. The minimum radius a_{min} should satisfy the equation

$$t_{cool} = t_{evap}, \quad (4)$$

where t_{cool} is the time scale of cooling of the postshock hot gas and t_{evap} is the time scale of complete evaporation of the particle, respectively. Since these two time scales depend mainly on the shock velocity v_s, preshock number density n_{pre}, and precursor radius a_{gr}, we can obtain a_{min} by solving Eq. (4) for given v_s and n_{pre}.

First, we estimate t_{cool}. Behind shock waves, the gas is cooled below 10^4 K or less due to Lyα emission. If we assume that the main molecular coolants are not destroyed by shock waves (or very fast molecular formation occurs after once these molecules are destroyed), the gas cools more effectively due to the molecular cooling. In this case, t_{cool} has only a weak dependence on v_s and n_{pre}, and becomes about 200 sec.

Second, t_{evap} is calculated as follows. After the drag heating finishes, the particle temperature T_{gr} is determined by the balance between some heating/cooling mechanisms; the heating due to gas-particle energy transfer, the radiative cooling, and the latent heat cooling due to the evaporation. We express this temperature T_{eq}. Substituting this T_{eq} to Eq. (1), the evaporation rate at this temperature is determined. Then, t_{evap} can be estimated by

$$t_{evap} = \frac{a_{gr}\rho_{gr}}{3J_{evap}}. \tag{5}$$

Detailed procedure is as follows:

1. Set v_s and n_{pre}.
2. Give "provisional" a_{gr}.
3. Solve the balance between the heating/cooling mechanisms on precursor particles.
4. Calculate t_{evap} using Eq. (5).
5. Compare t_{evap} with t_{cool} (~ 200 sec).
6. Check Eq. (4).

If Eq. (4) is not satisfied, return to step 2. We repeat this loop until Eq. (4) is satisfied, and can finally obtain a_{min}. In Fig. 2, the minimum sizes a_{min} are presented by three dashed lines labeled "2000 K", "4000 K", and "8000 K". These labels stand for the temperatures of the postshock hot gas used in the simple consideration. Particles plotted below these lines cannot survive the postshock hot gas with the specified gas temperature. We call these dashed lines "lines of survival" in this study. The numerical results show that symbols distribute above the lines of survival. Though there are some symbols located below lines of survival, all of them suggest that they have evaporated to 1/100 or less in their sizes.

Maximum size. A solid line represents the maximum size of molten particles a_{crit} above which a molten particle is destroyed by the ram pressure in the postshock gas [5]. Since this mechanism is not taken into account in our calculations as the particle destroying mechanism, particles plotted above the critical line a_{crit} may not be able to survive.

Summary: We simulate chondrule formation by the shock wave heating. The physical processes that we take into consideration in postshock hot gas are nonequilibrium chemical reactions and the thermodynamical evolutions of precursor particles, including the shrinkage due to the evaporation. We find the following points:

- There is the critical size of precursor particles below which no chondrule can be formed. This critical size is about 1 – 10 μm and this value is consistent with the size distribution of chondrules in CO chondrites.
- These numerical results are comprehensible by our simple analysis that compares the timescales of cooling of postshock hot gas and vanishing of precursor particle due to the evaporation.

These results suggest that the shock-wave heating model can explain the minimum chondrule radius naturally.

References: [1] Eisenhour D. D. (1996) *Meteoritics & Planet. Sci. 31,* 243-248. [2] Shapiro P. R. and Kang H. (1987) *Astrophys. J. 318,* 32-65. [3] Iida A. et al. (2001) *Icarus 153,* 430-450. [4] Miura H. et al. (2002) *Icarus 160,* 258-270. [5] Susa H. and Nakamoto T. (2002) *Astrophys. J. 564,* L57-L60.

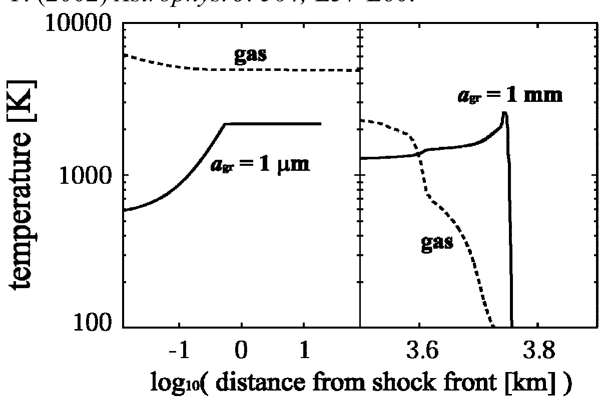

Figure 1: Temperature evolutions of the gas and dust particles with a_0 = 1 μm (left panel) and a_0 = 1mm (right panel) in the postshock region. The shock velocity and the preshock gas density are v_s = 15 km s^{-1} and $n_{pre} = 10^{13}$ cm^{-3}, respectively.

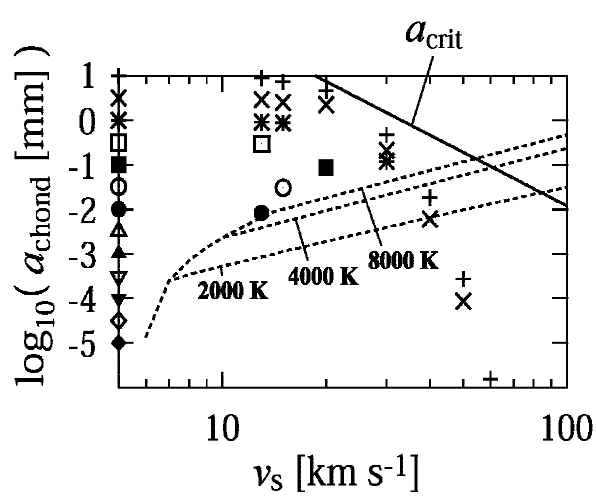

Figure 2: Final chondrule radius formed by shock-wave heating. The preshock number density is n_{pre} = 10^{13} cm^{-3}.