POSSIBLE SIZE OF PORPHYRITIC CHONDRULES IN SHOCK-WAVE HEATING MODEL

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Introduction: Chondrules are thought to have formed through some flash heating events in the early solar nebula. Shock wave heating model is now considered to be one of the most plausible models for chondrule formation. Some studies, assuming a homogeneous temperature distribution in dust particles, have shown that the model can explain various observations of chondrules [e.g., 1-6].

However, the temperature distribution in the dust particles can be inhomogeneous in the shock-wave heating model, because the dust particle is heated first from the surface by the gas frictional heating and then the inside is heated by the heat conduction. Also, the gas frictional heating works only on the upstream side of the particle. Thus, the dust particles should start to melt from the surface on the upstream side of the dust particle [7]. Kato, Nakamoto, and Miura [8] have used an analytic method and shown that when the particle is partially molten and a liquid mantle is present on a solid core, the stripping of the liquid surface due to the gas flow can take place. But the temperature distribution in the particle and the temperature dependence of the viscosity are not taken into account in their study.

Porphyritic chondrules (PC) are thought to have experienced the temperature 200K or more below the liquidus temperature [9]. The viscosity of material below the liquidus temperature is usually high, and it may be difficult to strip off a highly viscous liquid surface from the particle. So the stripping of the liquid surface may not take place in the case of PC. In this study, we first obtain the temperature and viscosity distributions in the dust particles by solving a three-dimensional heat conduction equation. Then, we discuss the stripping of the liquid surface from the particle and the possible size of PC.

Model: For simplicity, we assume that the dust particle is perfectly spherical, the deformation of the dust particle due to the gas ram pressure is negligible [8], the dust particle consists only of forsterite, and the temperature of radiation field in the post-shock region is T_0 = 1000 K. At the surface of the dust particle, we take into account three energy flows; the heat exchange between gas and dust particles, the thermal emission of the dust particle, and the absorption of the ambient radiation. The energy received at the surface of the dust particle is conducted into the particle following the heat conduction equation, which is given by $\partial T / \partial t = a \nabla^2 T$, where a and T are the temperature conductivity and the temperature in the dust particle, respectively. In addition, we take into account following three effects: (1) temporal variation of frictional heating due to the velocity decrease, (2) absorption of the latent heat in a temperature range between the solidus T_{sol} = 1500K and the liquidus T_{liq} = 1900K, and (3) rotation of the dust particle induced by the gas flow. And we use viscosity data of lava from Mt. Mihara, Mauna Loa, and Mauna Kea for a melt viscosity model.

Results: Figure 1 shows the temperature distribution in the equatorial plane of the dust particle. In this case, the particle radius is r_s = 5 mm, the shock velocity is v_s = 12 km s^{-1}, the density of gas in the post-shock region is n_g = 2.0x10^{14} cm^{-3}, and the rotation frequency is f = 0 rotation s^{-1} (panel a) and f = 100 rotation s^{-1} (panel b), respectively. We can see that the temperature at the front-side (or the surface, when the rotation is present) of the dust particle is higher than that of the backside (center). So the viscosity of the front-side (surface) is lower than that of the backside (center).

To strip off the liquid surface, the liquid part of the particle should move relative to the solid part. The timescale of the liquid flow could be evaluated using the timescale of the circulation in the liquid mantle obtained in the analytic solution [10], which is given by, $\tau_{flow}(T)$ = 0.51 sec ($\eta(T)$ / 1.3 poise) (p_{fm} / 1150 dyne cm^{-2})$^{-1}$, where p_{fm} and $\eta(T)$ represent the ram pressure and the viscosity, respectively. On the other hand, the stripping should finish within a period when the liquid and solid parts coexist. We define the timescale $\tau_{duration}(T)$ as a difference between the time when the temperature at a part in the particle reaches the given temperature T and the time when all the part in the particle reaches T. Then, one may think that $\tau_{flow} < \tau_{duration}$ is a condition for the stripping of the liquid surface. Figure 2 shows τ_{flow} and $\tau_{duration}$ as a function of the temperature. Parameters are the same as Fig 1(a). We can see that as the temperature rises, the viscosity falls, and the condition $\tau_{flow} < \tau_{duration}$ is met. If the temperature does not reach near the liquidus temperature, the stripping can hardly occur, because the temperature dependence of τ_{flow} is stronger than that of $\tau_{duration}$ so the viscosity in the liquid part increases drastically as the temperature decreases.

Discussion: We anticipate the formed structure of chondrules by using the temperature distribution in the particles at the moment when the lowest temperature inside the particle reaches the temporal peak temperature. Results for dust particles whose initial radius is 5 mm are summarized in Figure 3. When the input energy is not enough (corresponding to lower-left region of the figure), the stripping can not occur because the temperature is low and the viscosity is high, while the stripping can occur if the input energy is large enough to make the temperature sufficiently high (upper-right region). We can see that when the rotation is present (panel b), PC can be formed without stripping (square), because the rotation reduces the inhomogeneity of the temperature in the particle. This means that 5 mm-sized PC can be formed in the shock-wave heating model, if the precursor of 5 mm in radius is present and the rotation is induced. According to our numerical results and estimates based on an analytical discussion, critical radii below which PC can be formed without suffering stripping are about 4 mm (no rotation) and 25 mm (with rotation), respectively. Those critical radii are larger than those of natural porphyritic chondrules. Thus, at least in terms of PC sizes, the shock-wave heating model is consistent with observations.

Summary: By solving the heat conduction equation, the temperature distribution in the dust particle heated by the gas flow has been obtained and whether the stripping of the liquid surface due to the gas flow can occur or not has been examined with the melt viscosity as a function of the temperature. And the possible size of porphyritic chondrules (PC) has been discussed. What we have found are as follows.

1. If the temperature does not reach near the liquidus temperature, the stripping of the liquid surface can hardly occur, because the viscosity in the liquid part increases drastically as the temperature decreases.
2. The critical possible size of PC expected by the shock-wave heating model is larger than the size of natural PC. Thus, the shock-wave heating model is consistent with observations in terms of PC sizes.

References: [1] Desch S. J. *et al.* (2005) in *Chondrites and the Protoplanetary Disk*, 849-872. [2] Iida A. *et al.* (2001) *Icarus* **153**, 430-450. [3] Susa H. and Nakamoto T. (2002) *ApJ* **564**, L57-L60. [4] Miura H., Nakamoto T., and Susa H. (2002) *Icarus* **160**, 258-270. [5] Desch S. J. and Connolly H. C. Jr. (2002) *M&PS* **37**, 183-207. [6] Ciesla F. J. and Hood L. L. (2002) *Icarus* **158**, 281-293. [7] Yasuda S. and Nakamoto T. (2005) *LPI* **36**,1252. [8] Kato T., Nakamoto T., and Miura H. (2005), submitted. [9] Cohen B. A., Hewins R. H., and Yu Y. (2000) *Nature* **406**, 600-601. [10] Sekiya M., Uesugi M., and Nakamoto T. (2003) *Progress of Theoretical Physics* **109**, 717-728.

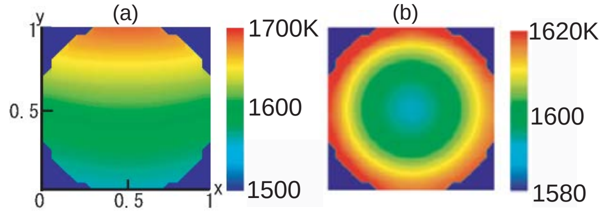

Figure 1: Temperature distribution in the equatorial plane of the dust particle. Parameters are $r_s = 5$ mm, $v_s = 12$ km s^{-1}, $n_g = 2.0\times10^{14}$ cm^{-3}, and rotation frequency $f = 0$ s^{-1} (panel a) and $f = 100$ s^{-1} (panel b), respectively. The gas particles hit on the upper half of the dust particle.

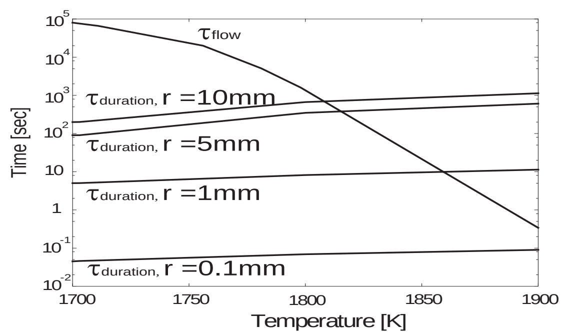

Figure 2: Timescales τ_{flow} and $\tau_{duration}$ in a temperature range from the PC forming temperature (1700K) to the liquidus temperature (1900K). Parameters are the same as Fig 1 (a).

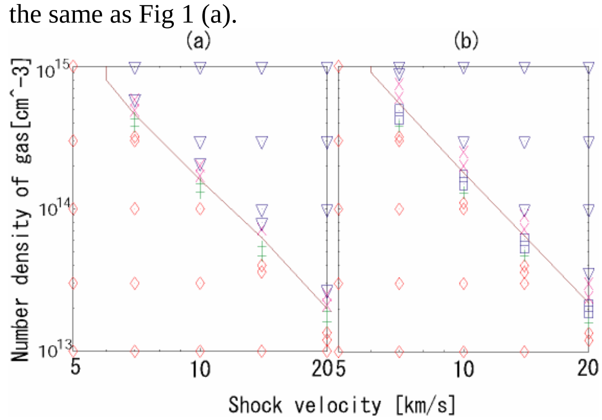

Figure 3: Structure of formed chondrules expected from temperature distribution at the moment when the backside of the dust particle reaches the peak temperature. The initial particle radius is $r_s = 5$ mm. Rotation frequency is assumed to be $f = 0$ s^{-1} (panel a) and $f = 100$ s^{-1} (panel b), respectively. Symbols denote no chondrule-like structure (diamond), PC in the front and no chondrule-like structure in the back (plus), PC without stripping (square), PC with stripping (cross), barred olivine (BO) in the front and PC in the back or BO in all (triangle). The line shows the boundary whether the stripping is expected to occur or not.