INHOMOGENEOUS TEMPERATURE DISTRIBUTION IN CHONDRULES IN THE SHOCK-WAVE HEATING MODEL. S. Yasuda[1] and T. Nakamoto[2], [1]Pure and Applied Sciences, Univ. of Tsukuba, Tsukuba, 305-8571, Japan (ysuda@het.ph.tsukuba.ac.jp), [2]Center for Computational Sciences, Univ. of Tsukuba.

Introduction: Chondrules are thought to have formed through some flash heating events in the early solar nebula. Shock wave heating model is considered to be one of the most plausible models for chondrule formation, because it can explain various observations of chondrules [e.g., 1-6]. Several studies of chondrule formation in a framework of the shock-wave heating model have been done. For example, the condition of shock parameters (shock velocity and pre-shock gas number density) appropriate for the chondrule formation is examined and revealed [2], and the maximal size of chondrules is estimated in terms of the shock wave heating model [3]. In all the studies for chondrule formation so far, it has been assumed that temperature distribution in the particle is homogeneous. However, in the shock-wave heating model, dust particles are heated first from the surface by the gas frictional heating and inside of the particle is then heated by the heat conduction. Also, the gas fricitional heating works only on the upstream side of the particle, i.e., the heating source distributes non-uniformly on the particle surface. Thus, it is naturally expected that the temperature distribution in the dust particle become inhomogeneous.

The purpose of this study is to examine how much the temperature difference appears in the dust particles in the shock wave heating model by numerically solving three-dimensional heat conduction equation.

Model: In order to calculate temperature distribution in the dust particle, we solve the time-dependent 3-D heat conduction equation, which is given by $T/\ t = a\ T$, where a and T are the temperature conductivity of silicate, the temperature in the dust particle, and $\ T$ is the Laplacian of T, respectively. 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 [7], and the temperature of radiation field in the post-shock region is $T_0 = 1000$ K. Also, we assume that, initially, the temperature in the dust particle is homogeneous and equal to the radiation field temperature in the post-shock region, i.e., $T(t=0) = T_0 = 1000$ K. At the surface of the dust particle, we take into account three energy flows as the boundary condition; the heating due to the gas drag, the radiation cooling due to the thermal emission from the dust particle, and the radiation heating due to the radiation field around the particle. In addition, we take into account following three effects: (1) temporal variation of drag heating due to the decrease of the gas drag force as the time proceeds, (2) rotation of the dust particle, and (3) the latent heat of the particle at the time of the phase change.

Results: Figure 1 shows the evolution of the temperature at two antipodal points on the equator of the dust surface and at the center of the dust particle. In this case, the radius of the dust particle is $r_s = 1$ mm, the shock velocity is $v_s = 12$ km/s, the density of gas in the pre-shock region is $n_g = 1.0 \times 10^{14}$ cm^{-3}, and the rotation frequency is $\omega = 0.1$ s^{-1}. The melting point of the dust particle is assumed to be $T_m = 1700$ K. According to [2], shock waves with these parameters can form chondrules. From Figure 1, we find that the temperature distribution in the dust particle is inhomogeneous. For example, at $t = 5$ sec, the back side of the dust is solid, while the front side is already melted; this dust particle melts partially. The maximum temperature difference between the front and the back is $\Delta T_{fb} = 230$ K and that between the front and the center is $\Delta T_{fc} = 160$K. In this case, $\Delta T_{fb} > \Delta T_{fc}$, and the distribution of the temperature is plane-parallel or *layered*, because the dust particle is heated only one side.

Figure 2 shows a result with the same parameters in Figure 1 case except for $\omega = 10$ s^{-1}. Though the temperature distribution is still inhomogeneous, $\Delta T_{fb} = 43$ K and $\Delta T_{fc} = 57$ K. In this case, $\Delta T_{fb} < \Delta T_{fc}$, and the distribution of the temperature is onion-like or *spherically symmetric*, because the whole surface of dust particle is heated due to the rotation.

We have found that two types of temperature distribution, the *layered* and the *spherically symmetric*, appear in the heated dust particles depending on the rotation frequency. Figure 3 shows ΔT_{fb} and ΔT_{fc} as functions of rotation frequency ω. We find that in the case of Figure 1 and 2, the temperature distribution switches from the *layered* to the *spherically symmetric* at about $\omega = 4$ s^{-1}. We define the critical frequency ω_c as the frequency at which the type of the temperature distribution switches; so $\omega_c = 4$ s^{-1} in the case. Additionally, it has been found that in the *spherically symmetric* case, the temperature difference between two antipodal points on the equator, ΔT_{fb}, approaches to 0 K as the rotation frequency ω increases, while the temperature difference between the surface and the center, ΔT_{fc}, remains finite. The minimum of ΔT_{fc} is about 40K, even when the rotation is very fast.

Disscussion: From the calculations, we have found that the inhomogeneous temperature distribution appears in the dust particle and there is the critical rotation frequency ω_c which determines the type of the temperature distribution. We can understand these results using following three timescales, (1) timescale of the heaing ($t_h = \tilde{n}_d c r_s T / \tilde{n}_g v_s^3$), where $\tilde{n}_d$ is the density in the dust particle and c is the specific heat, (2) timescale of rotation ($t_r = 1/\omega$), and (3) timescale of heat conduction ($t_c = r_s^2/a$). If $t_h < t_c < t_r$ or $t_h < t_r < t_c$, the distribution of temperature becomes *layered* one, because the heating is so efficient that only the front side of the particle is heated. Neither the input energy is transferred to the inside, nor the other side is heated efficiently, since the rotation is slow. On the other hand, if $t_r < t_h < t_c$, the *spherically symmetric* temperature distribution appears, because the fast rotation smoothes out the non-uniform distribution of the heating source at the surface. Other patterns of time scale orders did not appear in the chondrule forming shock wave cases.

Summary: We examined what kind of temperature distribution in the dust particle appear in the shock-wave heating model. We took into account some physical effects: non-uniform gas frictional heating on the surface, the heat conduction in the particle, the radiative cooling/heating at the surface, and the rotaiton of the particle. What we found are as follows.

1. The dust particles almost always have inhomogeneous inner temperature distribution.
2. Two types of temperature distribution, *layered* and *spherically symmetric*, were observed, depending on the rotation frequency. When the rotation is faster than the critical rotation frequency, the distribution of temperature becomes *spherically symmetric*.
3. Even when the rotation is fast enough and the temperature distribution is *spherically symmetric*, the finite temperature difference between the surface and the center of the dust particle remains.
4. Results mentioned above can be understood in terms of ratios among three timescales; the time scales of heating, rotation, and conduction. If $t_h < t_c < t_r$ or $t_h < t_r < t_c$, temperature distribution becomes *layered*, while if $t_r < t_h < t_c$, it becomes *spherically symmetric*.

The inhomogeneous temperature distribution could affect chemical and mineralogical properties of chondrules. Detailed investigations for these points should be done in the future.

References: [1] Jones R. H. et al. (2000) in *Protostars and Planets IV*, 927-962. [2] Iida A. et al. (2001) *Icarus 153*, 430-450. [3] Susa H. and Nakamoto T. (2002) *ApJ 564*, L57-L60. [4] Miura H. et al. (2002) *Icarus 160*, 258-270. [5] Miura H. and Nakamoto T. (2005) *Icarus*, in press. [6] Miura H. and Nakamoto T. (2005) Antarctic Meteorite Research, in press. [7] Uesugi M. et al. (2003), *Earth Planets Space* 55, 493-507.

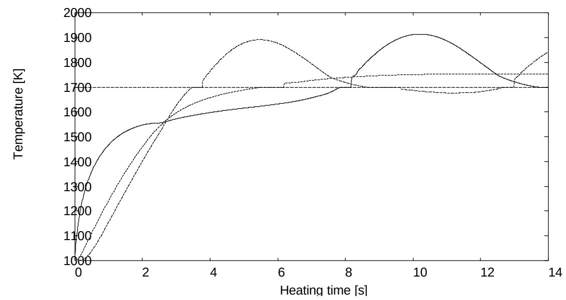

Figure 1: Temperature in the dust particle vs. heating time. Parameters are r_s = 1 mm, v_s = 12 km/s, n_g = 1.0×10^{14} cm^{-3}, and ω = 0.1 s^{-1}. Solid, dash-dotted, dashed, and dotted curves represent temperatures at two antipodal points on the equator, at the center of the dust, and the melting point, respectively.

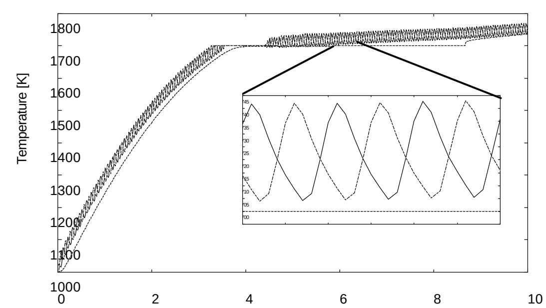

Figure 2: Temperature in the dust particle vs. heating time. Parameters are the same with Figure 1 except for the rotation frequency, ω = 10 s^{-1}.

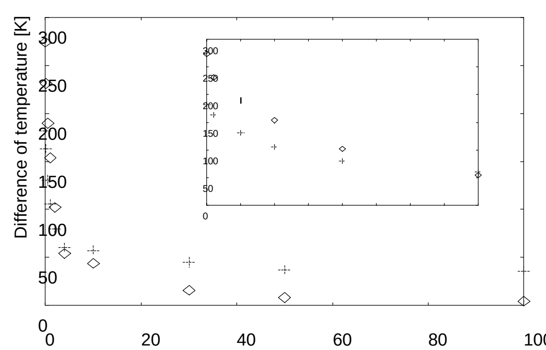

Figure 3: The maximum different of temperature vs. rotational velocity. Diamonds represent the maximum temperature difference between the front and the back, ΔT_{fb}, and pluses represent the maximum temperature difference between the front and the center ΔT_{fc}.