

APPROPRIATE SHOCK WAVES FOR CHONDRULE FORMATION: HEATING RATE AND COOLING RATE CONSTRAINTS. H. Miura¹ and T. Nakamoto², ¹Univ. of Tsukuba (miurah@ccs.tsukuba.ac.jp), ²Univ. of Tsukuba (nakamoto@ccs.tsukuba.ac.jp).

Introduction: The absence of isotopic fractionation in chondrules suggests that chondrules have to be heated rapidly ($>10^4$ K/hr) at a temperature range of 1273-1573 K [1]. Dust aggregates that have never melted before are thought to be fluffy. When such aggregates are heated, the isotopic fractionation should occur associated the evaporation from inside of fluffy aggregates. If the heating rate is slow, it is impossible to suppress the isotopic fractionation. On the contrary, since once molten dust particles are not fluffy, there is no need to heat them rapidly.

On the other hand, chondrules have to cool at an appropriate speed (~ 10 -3000 K/hr) in order to reproduce their texture (e.g., porphyritic, barred olivine, and so forth) [e.g., 2]. The shock-wave heating model taking into account the radiation transfer can explain the appropriate cooling rate [2, 3]. However, it is unclear whether or not the heating rate of chondrules in those models is rapid enough to suppress the isotopic fractionation.

In this study, we numerically simulate the shock-wave heating model taking into account the radiation transfer (both the dust thermal continuum emission and the line emission of gas molecules) and discuss the chondrule formation scenario which satisfies both constraints: the rapid heating rate and the appropriate cooling rate.

Shock-Wave Heating 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 the gas in the pre-shock region n_0 are principal parameters for the shock-wave heating model (see Figure 1). We calculate the structure of the gas flow (both pre- and post-shock regions) taking into account non-equilibrium chemical reactions. Equations describing precursor grain evolution are equations of motion, energy, and radius shrinkage by evaporation [4].

Radiation transfer. The transfer of dust thermal radiation has been treated in [2, 3]. However, they did not take into account the line emission of gas molecules. In a real situation, some amount of line emission emitted in the post-shock region can escape toward the pre-shock region. Since the line emission also heats the dust particles in the pre-shock region, we have to take into account the transfer of the line emission. (Note that the shock-wave heating model by [5] took into account the line emission from gas

molecules, though the heating process of the dust particle due to the thermal radiation from other dust particles was ignored. The model by [5] reproduces the appropriate cooling rates of chondrules, but the heating rate in the pre-shock region was not examined.) Regarding absorption by gas molecules, we use the photon escape probability method [6]. Regarding absorption by dust particles, we solve the radiation transfer equation precisely.

Precursor dust particle model. We assume two size distribution models for precursor dust particles; power-law distribution and lognormal one. The dust to gas mass ratio in the pre-shock region is changed. We assume that the size range of dust particles is from $0.01\mu\text{m}$ to 1cm , and calculate time evolution of those particles simultaneously with gas dynamics.

Results: We mainly examined thermal histories of chondrule-sized dust particles (radius = $250\mu\text{m}$). In each calculation, we obtained the heating rate at the heating phase and the cooling rate at the re-solidification phase. We plot these results as a function of the optical depth of the pre-shock region.

Heating rate. Figure 2 shows heating rates at the temperature range of 1273-1573 K. Each color of symbol corresponds to the one of cases A through D in Fig. 1. It is clearly found that there is a critical optical depth that separates the rapid heating ($\sim 10^6$ K/hr) and the slow heating (~ 100 -1000 K/hr). Heating rate of the rapid heating cases is large enough to suppress the isotopic fractionation, while that of the slow heating cases is too slow to do that. In the case A, which is the similar shock condition to the shock waves generated by the gravitational instability in the protoplanetary disk [2], it is possible to suppress the isotopic fractionation only if the optical depth is smaller than about unity. On the other hand, in the case D, which is the similar condition to the shock waves induced by X-ray flares [7], since the shock wave is optically thin enough, the heating rate is large enough to suppress the isotopic fractionation with any dust conditions (dust to gas mass ratio and dust size distribution).

Cooling rate. Figure 3 is the same as Fig. 2 except the vertical axis representing the cooling rates in the re-solidification phase. Each symbol corresponds to the symbol in Fig. 2. We find that the cooling rates are high ($>$ a few 1000 K/hr) in the optically thin environment and low ($<$ 100 K/hr) in the optically thick environment. In optically thick

environments, since the blanket effect works well in the pre-shock region, the radiation heating for dust particles becomes effective. Thus, dust particles are kept in the re-solidification phase for a long time and the cooling rate becomes appropriate value. This effect was shown by [2]. On the other hand, an optically thin environment, e.g., low-density and high-velocity shock waves (case D), can produce appropriate cooling rates, too. In those low-density shock waves, the stopping time scale of dust particles is long due to the low gas density. Thus, the drag heating continues for longer time and dust particles cool gradually as the relative velocity between the gas and dust particles decreases slowly. This effect was shown by [5].

Discussion: In order to produce chondrules, the heating mechanism should satisfy at least two constraints; the rapid heating ($>10^4$ K/hr) and the appropriate cooling (~ 10 -3000 K/hr). The model of [2, 3] succeeded in reproducing the appropriate cooling rate, however, their results do not satisfy the rapid heating constraint. The reason is that the optically thick condition, which leads to the slow cooling in the post-shock region, should cause the slow heating in the pre-shock region. We need other shock wave model, which satisfies the rapid heating in order to suppress the isotopic fractionation. One possibility is the optically thin environment for the gravitational instability shock waves. If the spatial scale of shock waves is 10^5 km, the dust to gas mass ratio less than about 0.03 satisfies the rapid heating condition. However, if the spatial scale is 10^6 km, it is impossible to suppress the isotopic fractionation even when the dust to gas mass ratio is 0.01, which is a standard value for a minimum mass solar nebula model. On the other hand, the X-ray flare induced shock waves [7] satisfy the rapid heating constraint even when the dust to gas mass ratio is 10 times greater than the standard value.

To summarize, it seems difficult to reproduce chondrules by the shock waves generated by the gravitational instability of the protoplanetary disk. On the contrary, shock waves generated by the X-ray flares [7] seem to satisfy both constraints: the rapid heating and the appropriate cooling rate.

References: [1] Tachibana S. and Huss G. R. (2004) *GCA*, in press. [2] Desch S. J. and Connolly H. C. (2002) *MAPS* 37, 183-207. [3] Ciesla F. J. and Hood L. L. (2002) *Icarus* 158, 281-293. [4] Miura H. and Nakamoto T. (2005) *Icarus*, in press. [5] Iida A. et al. (2001) *Icarus* 153, 430-450. [6] Neufeld D. A. and Kaufman M. J. (1993) *ApJ* 418, 263-272. [7] Nakamoto T. et al. (2004) *LPS XXXV*, Abstract #1821.

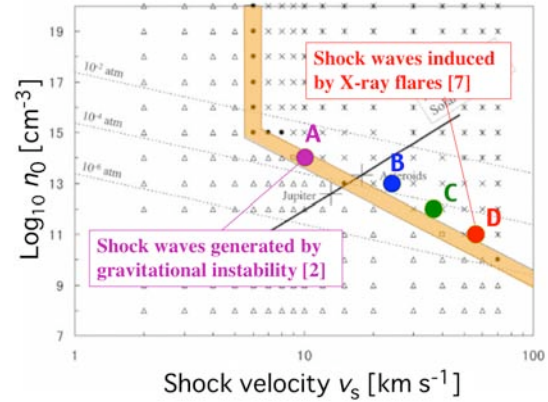


Figure 1: Shock conditions A through D examined in this study. Orange region stands for appropriate shock condition for chondrule formation [8].

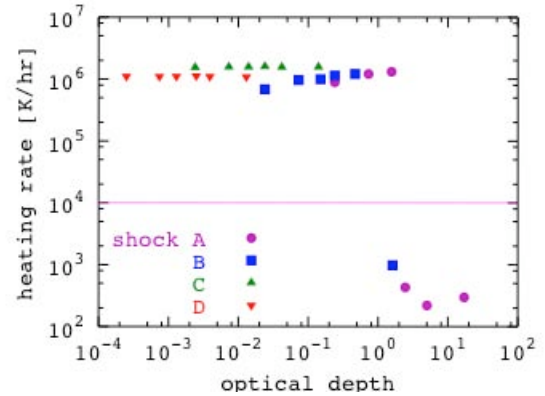


Figure 2: Heating rate of chondrules are plotted as a function of optical depth of the pre-shock region. Solid line means lower limit below which isotopic fractionation should occur.

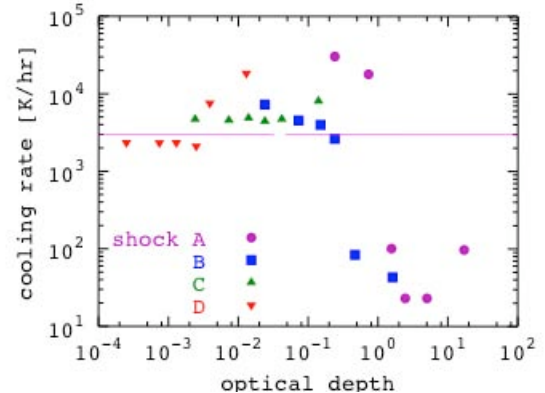


Figure 3: Cooling rate in the re-solidification phase as a function of optical depth. Solid line means the upper limit above which typical chondrule texture should not be reproduced.