SHOCK-WAVE HEATING MODEL FOR CHONDRULE FORMATION: APPROPRIATE CONDITIONS IN PROTOPLANETARY DISK

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Abstract Very rapid heating is required for chondrule formation based on discussions of the isotopic fractionation data in measured chondrules. In the case of shock-wave heating model, the gas drag heating which works in the post-shock region can heat dust particles so rapidly. However, dust particles are also heated in the pre-shock region by radiation. The main sources of radiation are gas and dust particles in the post-shock region. Can the shock-wave heating form chondrules? If yes, what conditions are appropriate for chondrule formation? To answer these questions, we develop a new simulation code taking into account the radiation transfer for gas line emission and dust continuum emission. Our calculation results show that the optically thin environment is appropriate for chondrule formation. For example, shock-waves induced by the X-ray flare (talk of Taishi Nakamoto in this conference, #9034) seem to show a good agreement with the heating rate constraint.

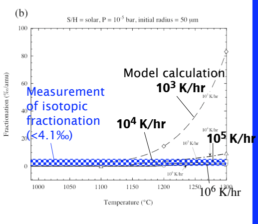
Introduction, Model, & Purpose

MYSTERY OF CHONDRULES

It is believed that chondrules have experienced very high temperature event that silicate component of them have melted (>1600K). For such high temperature phase, it is expected that the isotopic fractionation takes place associated with the evaporation of the dust component. However, in the measured chondrules, there is no evidence of the isotopic fractionation expected from the kinetic evaporation model (Tachibana & Huss 2004)。

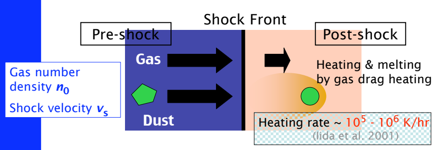
ISOTOPIC FRACTIONATION & HEATING RATE

It is considered that isotopic fractionation of sulfur occurs significantly in a temperature range of 1273-1573K (Tachibana & Huss 2004). To suppress the isotopic fractionation, the heating rate in the temperature range should be rapid enough. According to Tachibana & Huss (2004), the required heating rate to suppress the isotopic fractionation should be larger than about 10^4 K/hr.

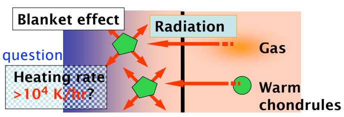


Isotopic fractionation by kinetic evaporation model (Tachibana & Huss 2004). Horizontal axis is dust temperature. Heating rate is constant in this calculation. This panel shows results for heating rate of 10^3, 10^4, 10^5, and 10^6 K/hr, respectively.

SHOCK-WAVE HEATING MODEL

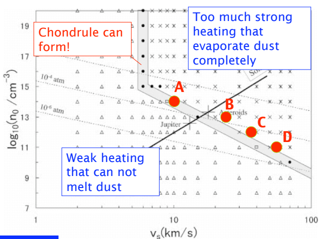


Gas drag heating : After passing through shock front, relative velocity between dust and gas is generated and gas drag heats dust particles. Its heating rate is large enough to suppress isotopic fractionation.



Heating by radiation : In post-shock region, gas and chondrules emit radiation. Some fraction of the radiation goes toward pre-shock region and heats dust particles in that region. Additionally, blanket effect takes place in pre-shock region. By the effect, radiation intensity becomes stronger.

Figure 1. Regarding the gas drag heating, some detailed numerical simulations have been done. Especially, Iida et al. (2001) investigated the chondrule forming shock conditions as a function of n_0 and v_s.



PURPOSE OF THIS STUDY

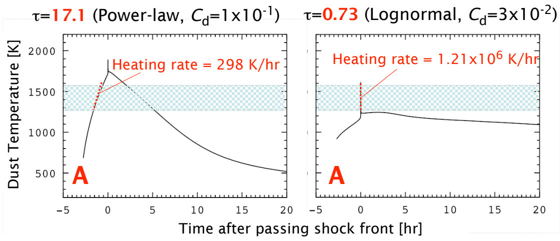
Our purpose is to calculate the heating rate of chondrule in the pre-shock region. We develop a new simulation code (Iida et al. 2001 + radiation transfer) and calculated for chondrule-forming shock conditions (A, B, C, and D in Figure 1). We change the dust to gas mass ratio and size distribution of dust particles which are directly related to the optical depth in pre-shock region.

Dust/gas mass ratio C_d	Dust size distribution
0.10	Power-law
0.03	Lognormal
0.01	

Results & Discussion

HEATING RATE

Thermal histories of the optically thick case (left panel, τ=17.1) and the optically thin case (right panel, τ=0.73)



The blanket effect works well in pre-shock region because of the optically thick environment. The dust temperature at the shock front reaches 1722K. The heating rate is calculated to be 298 K/hr. In this case, it is expected that the isotopic fractionation should occur.

The blanket effect does not work well. The dust temperature at the shock front is only 1201K. After passing through shock front, dust particle is rapidly heated by the gas drag heating and melted. The heating rate is large enough (~1.21x10^6 K/hr) to suppress the isotopic fractionation.

LIMITATION OF OPTICAL DEPTH

We discuss how to determine critical value of optical depth below which dust temperature in the preshock region is less than 1273K.

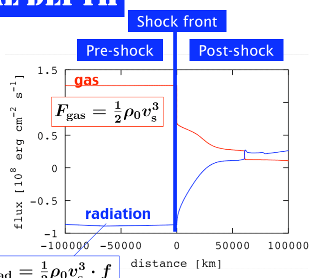
In the optically thick environment, radiation flux produced by temperature gradient (in this case, "dust" temperature gradient) is given by radiative diffusion approximation;

$$F_{\rm rad}(\tau) = -\frac{4\sigma}{3}\frac{\partial T^4}{\partial \tau} \quad (1)$$

Assuming $F_{\rm rad}$ = constant and integrating eq. (1) from boundary to shock front, we obtain the dust temperature at the shock front $T_{\rm SF}$;

$$T_{\rm SF}^4 = \frac{1+3\tau}{4\sigma}F_{\rm rad} \quad (2)$$

In order to suppress the isotopic fractionation, $T_{\rm SF}$ should be below 1273K. From eq. (2), upper limit of optical depth t can be estimated.

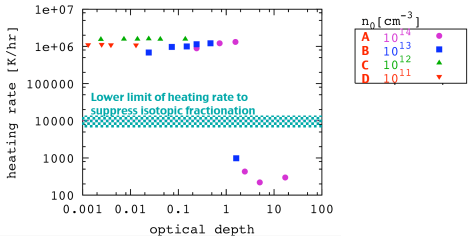


$$F_{\rm rad} = \frac{1}{2}\rho_0 v_s^3 \cdot f$$
$$f = 0.5 - 0.9$$

f is the ratio of the ratiation flux back from the shock front to the gas energy flux going toward the shock front.

	shock condition		upper limit of optical depth	
	n_0 (cm^{-3})	v_s (km s^{-1})	$f = 0.5$	$f = 0.9$
A	10^{14}	10	1.65	0.77
B	10^{13}	22	1.53	0.70
C	10^{12}	35	4.30	2.24
D	10^{11}	55	11.6	6.30

Table 1. Upper limit of pre-shock optical depth estimated by eq. (2). From our numerical calculation results, we find that f ~ 0.5-0.9 (depends on n_0, v_s, size distribution, and C_d). If the pre-shock optical depth is larger than upper limit, dust temperature exceeds 1273K by the blanket effect in the pre-shock region. For such optically thick condition, the heating rate becomes very small.



Heating rate plotted as functions of optical depth. If the optical depth is larger than the upper limit of optical depth listed in Table 1, the heating rate decreases drastically. In cases of shock conditions C and D, all cases show very rapid heating (~10^6 K/hr), because the optical depth of all cases is smaller than the upper limit of optical depth for each case.

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