Constraints on the Heating and Cooling Processes of Chondrule Formation

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Constraints on the temperature history of chondrules are examined on the basis of petrological observations. The chondrule formation processes are divided into two parts, i.e., the heating of pre-chondrule particles by external heat sources, and the cooling of chondrules surrounded by solar nebula. Relations between the duration of the surface temperature and the maximum attainable temperature inside chondrules are obtained from thermal diffusion calculations for externally heated pre-chondrule particles. It is concluded that the duration of each heating event should be less than 0.01 sec for chondrules that have a typical radius of 0.3 mm and include relict minerals. The duration of each heating event could not vary widely because of the limited size distribution of chondrules and the common occurrence of relict minerals in chondrules. By assuming radiative conduction cooling of the gas-dust mixture from near the liquidus of olivine to the ambient temperature of solar nebula, the cooling rate becomes 1 to 0.1 K/sec for a radius of about 600 m, provided that the chondrules and the solar nebula surrounding them cool as a whole. The number density of pre-chondrule particles would be so large that mutual collisions of melted or partially melted chondrules would occur frequently with low relative velocity in the central part of the chondrule-forming region. Chondrules thus produced would be reheated at least several times and would have complex thermal histories because of the wide variety of cooling processes. These conditions of the temperature history of chondrule evolution seem to be concordant with the "lightning" discharge model, although other mechanisms cannot be excluded.

INTRODUCTION

Models of chondrule formation processes generally involve some violent and quick heating to melt silicate minerals followed by a rapid cooling (e.g., Smith, 1982). Quantitative loss of volatile elements (e.g., Larimer and Anders, 1967) suggests that chondrules were formed in the primordial solar nebula with an ambient temperature of some 550 K and pressure of 10^{-2} to 10^{-6} atm (e.g., Whipple, 1972). However, mechanisms of chondrule formation have been the subject of controversy because a variety of possible events could take place; for example, (1) fusion of dust or aggregate grains by the lightning discharge (Whipple, 1966; Cameron, 1966; Rasmussen and Wasson, 1982) or acceleration of electrons by the reconnection of interplanetary magnetic field (Sonett, 1979); (2) shock melting by high velocity collisions (Wasson, 1972; Whipple, 1972; Kieffer, 1975; Grossman *et al.*, 1979; King, 1982); and (3) direct condensation from the solar nebula or reheated nebula with infalling dust particles by shear friction or shock waves

(Wood, 1963, 1983; Wood and McSween, 1977; Podolak and Cameron, 1974; Cameron, 1982).

Among various mechanisms for the chondrule formation, melting of pre-existing solids would be favored from the petrological investigations including textures (e.g., Dodd, 1978; Ikeda, 1980; Christophe Michel-Lévy, 1981; Gooding and Keil, 1981) and chemical studies (Gooding *et al.*, 1980). The recent recognition of relict minerals in chondrules (Nagahara, 1981; Rambaldi, 1981; Rambaldi and Wasson, 1981, 1982) and a wide variety of cooling rates (a few to 10^{-4} K/sec) in dynamic crystallization experiments that reproduce chondrule-like texture (Blander *et al.*, 1976; Tsuchiyama *et al.*, 1980; Hewins *et al.*, 1981) contribute to restrict conditions of evolutional processes of chondrules. These observations appear to preclude direct condensation from the solar nebula and high velocity impact as mechanisms of chondrule formation (Lux *et al.*, 1981; Hewins, 1982) and throw light on the heating and cooling mechanisms of chondrule formation. This paper presents some constraints on the heating duration and the maximum temperatures experienced for the chondrule precursors and physical conditions from the requirements of observed cooling rates of melted or partially melted chondrules.

HEATING DURATION AND THE MAXIMUM TEMPERATURE

For a chondrule including a relict olivine, the melting of pre-chondrule materials occurs only partially from the surface. It is noteworthy that relict olivines exist mostly inside the chondrules and very few exist near the rims. The maximum attainable temperature should be lower than the liquidus of olivines for such a chondrule heated externally. The duration of heating events should

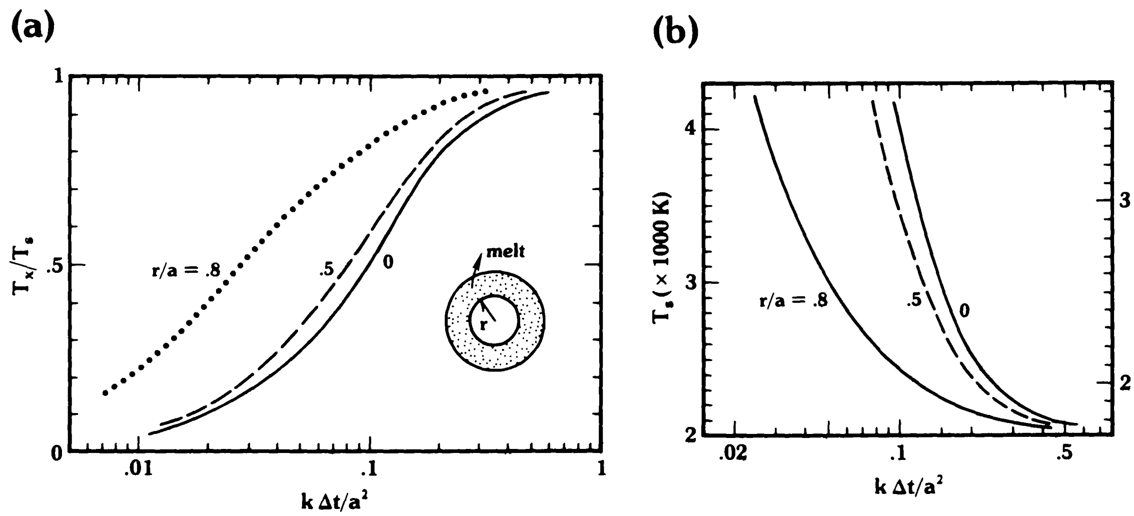

Fig. 1 **(a)** Normalized maximum attainable temperature (Tx/Ts) vs. the heating duration (k $\Delta t/a^2$) at radial distances (r/a) of 0.8, 0.5, and 0 for an externally heated chondrule. **(b)** The surface temperature (Ts) vs. the heating duration of Ts for liquidi of 2000 K (left-hand scale) and of 1700 K (right-hand scale).

have been limited if the surface temperature would exceed their liquidus. By assuming a constant radius (a) and thermal diffusivity (k) for externally heated spherical particles, a temperature distribution can be calculated (Carslaw and Jaeger, 1959). The relation between the duration of external heating (Δt) and the maximum attainable temperature (Tx) at a radial distance (r/a) has previously calculated with a radiation boundary condition (Miyamoto and Fujii, 1980; Fujii *et al.*, 1982). In this analysis, the surface temperature Ts is maintained constant during the time interval Δt, and is measured from the initial uniform temperature (i.e., ambient solar nebula). Figure 1a shows the maximum attainable temperature (Tx/Ts) vs. a non-dimensional heating duration of Ts ($k\,\Delta t/a^2$) for radial distances r/a of 0.8, 0.5, and 0. If the surface temperature (Ts) is 3000 K and the liquidus of olivine is 2000 K, the heating duration of Ts should be shorter than about 0.1 as illustrated in Fig. 1b, in which the left-hand scale for Ts corresponds to a liquidus of 2000 K and the right-hand to 1700 K, respectively. For a radius of 0.3 mm and a thermal diffusivity of 0.01 cm^2/sec, the actual duration becomes about 0.01 sec. It is, however, noted that this duration tends to infinity as Ts approaches to liquidus or between solidus and liquidus.

COOLING RATES OF CHONDRULES

From experimentally simulated textures of chondrules, the cooling rate ranges from a few to 10^{-4} K/sec at the temperatures between 1600 and 1200 C (Tsuchiyama *et al.*, 1980; Hewins *et al.*, 1981; Tsuchiyama and Nagahara, 1981; Planner and Keil, 1982). However, the cooling rate of isolated chondrules with a radius of about 0.3 mm is 1000 to 10 K/sec, when the ambient temperature is around 550 K. These are much faster than those observed in the simulation experiments. As a consequence, a "dense" gas is required to explain this discrepancy (e.g., Nagahara, 1982; Tsuchiyama *et al.*, 1982). We consider that the initial stage of chondrule formation could be responsible for the requirement of the observed cooling rates.

The radiative heat transfer depends highly on the absolute temperature and density of the gas surrounding chondrules. It may be likely that the radiation energy from the melted or partially melted chondrules is absorbed by the gas. In addition, by absorbing the radiation energy from external heat sources dust particles smaller than millimeter-size may have evaporated and have subsequently condensed within a shorter time scale than the cooling time of the surrounding gas-dust mixture. This process could have contributed to raising the temperature of the gas around the chondrules as well. Thus, cooling rates of chondrules appear to be controlled by the cooling of the gas-dust (chondrule) mixture as a whole. In the following, we consider cooling of the gas-dust mixture by radiative conduction with the approximation that the optical length of the gas-dust mixture is small in this medium, which has cylindrical symmetry for convenience. The high number density of dust particles and chondrules in the chondrule-forming region may also contribute to shortening the optical length.

The initial temperature (To) may be as high as the temperature of melted silicates at the inside of the cylindrical medium and as low as that of the solar nebula at the outside. By assuming a radiation cooling boundary condition (Carslaw and Jaeger, 1959), the temperature variations

(T/To) at the center (C) and the average one (A) are shown as a function of normalized elapsed time ($\hat{k}t/R^2$) in Fig. 2a, in which $\hat{k}$ and R are thermal diffusivity of the gas-dust mixture and radius of the medium, respectively. By differentiating temperature with respect to time, the variation of cooling rates ($\dot{T} \cdot R^2/To \cdot \hat{k}$) with elapsed time ($\hat{k}t/R^2$) is shown in Fig. 2b, in which $\dot{T}$ denotes the time derivative of temperature. The thermal diffusivity of the gas-dust mixture can be approximated by that of molecular hydrogen, and is about 60 m^2/sec for 1500 ~ 2000 K and 10^{-4} atm. The cooling rate at T ~ 1600 K (for To ~ 2000 K) is 1 to 0.1 K/sec when the radius R is about 600 m and the corresponding time is about 10 min.

DISCUSSIONS AND CONCLUSIONS

From the observations of the presence of relict minerals in chondrules with the most common texture (Nagahara, 1981; Rambaldi, 1981; Rambaldi and Wasson, 1981, 1982) and of volatile elements such as sodium (Tsuchiyama *et al.,* 1981), the maximum temperature of chondrules could not be very high for long duration. The duration of 0.01 sec for heating the surface above the

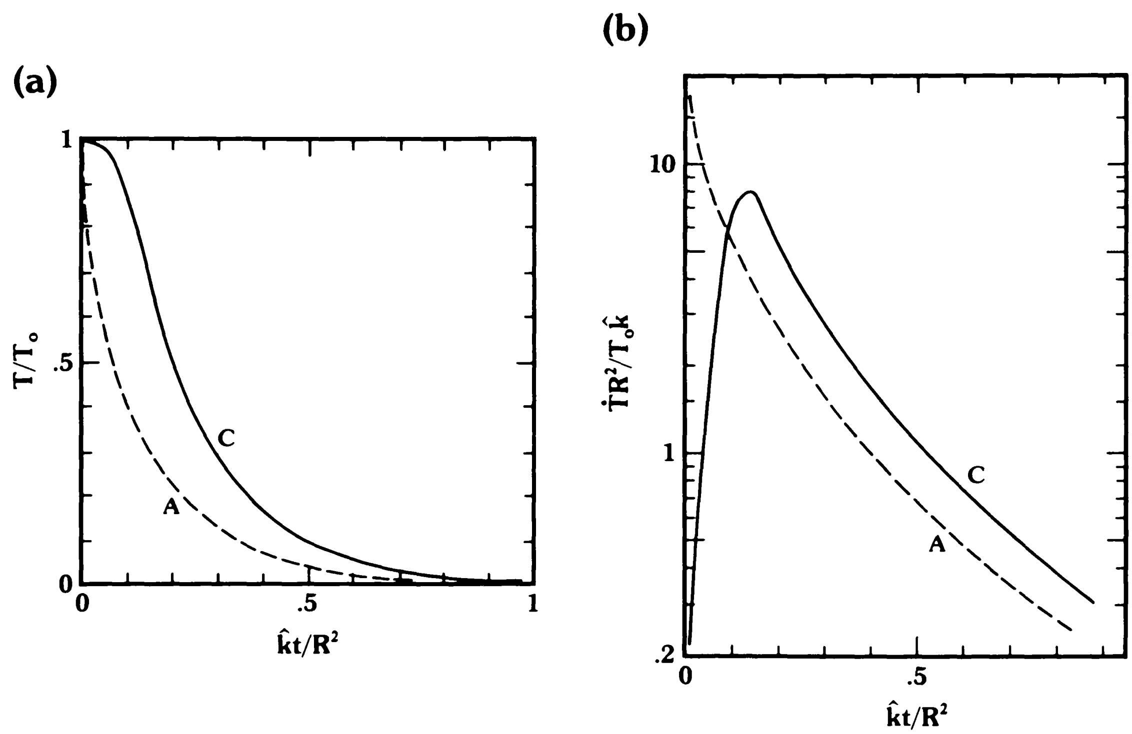

Fig. 2 **(a)** Temperature variations (T/To) of the cylindrical medium as a function of elapsed time ($\hat{k}t/R^2$), where To is the initial constant temperature and $\hat{k}$ and R are thermal diffusivity and radius of the medium, respectively. Labels A and C indicate the average temperature and the temperature at the center, respectively. **(b)** Cooling rates ($\dot{T} \cdot R^2/To \cdot \hat{k}$) of the medium. Other symbols are the same as in **(a)**.

liquidus temperature is a crude limit (Fujii *et al.*, 1982). Because only thermal diffusion was considered in this study, this limit may change by some amount. If the maximum temperature were between liquidus and solidus, there would be no limitation for its duration. It seems, however, unlikely to consider such a mechanism that can raise the temperature of pre-chondrule materials just between liquidus and solidus. Although the evaporation experiments may suggest longer heating duration, evaporation rates of sodium in chondrules are strongly influenced by the oxygen fugacity and the amount of superheat. As the fugacity is lower and temperature is higher, sodium is more easily evaporated from silicate melt and the required duration of the maximum temperature is far shorter under actual chondrule formation conditions than in experiments (Tsuchiyama *et al.*, 1981). Further investigations could make quantitative constraints on the heating duration from the evaporation rate of volatiles for chondrules without relict silicate minerals.

The obtained conditions could not specify the actual mechanism of heat sources to produce melt droplets, but could restrict the heating and cooling history by following a particular heat source. As an example of such a heat source, we examine the case of the "lightning" discharge model (Whipple, 1966). During the formation process of planetesimals with a mass of $10^{18} \sim 10^{20}$ g by gravitational instability of the dust layer (Goldreich and Ward, 1973), the lightning discharge could occur frequently throughout this layer. At this stage, dust particles have grown to about 0.1 mm in average size through sedimentation and accretion processes (Safronov, 1969; Kusaka *et al.*, 1970). These pre-chondrule dust particles would be so fluffy that the radiation energy emitted by lightning discharge could be effectively absorbed and could produce submillimeter-sized melted silicate particles within some distance from the lightning paths (Whipple, 1966). The heating duration of about 0.01 sec is about three orders longer than the duration of lightning in the Earth's atmosphere, but is concordant with the mechanism proposed by Sonett (1979). Because the pre-chondrule particle is assumed to be a solid spherule in this estimation, the limit of 0.01 sec for the heating duration may be an overestimate. The radiation energy would be more effectively absorbed for fluffy or sponge-like aggregates (Whipple, 1966). The temperature of such particles may increase more instantaneously than demonstrated in Fig. 1. If the lightning would occur in a turbulent solar nebula (Rasmussen and Wasson, 1982), radiated energy would be transported by the turbulent convection. However, it would be probable that pre-chondrules could be heated by radiation and part of the gas-dust mixture could cool by radiation conduction when the eddies in the turbulent nebula were far larger than a few kilometers.

If the primordial gas-dust mixture were not so dense that radiative heat transfer would be dominant, the cooling rate estimated by radiative conduction alone may be too slow. In the course of planetesimal formation by gravitational instability, dust particles would become concentrated in the central part and would be surrounded by a dense primordial nebula. We expect at some stage of this process that the radiative conduction would become dominant, although we could not quantitatively postulate actual values of the gas pressure and number density of pre-chondrule materials at this moment. Because of the probable occurrence of frequent heating events, the chondrules would have complex thermal histories, or would be reheated several times. Data for cooling history in the lower temperature range are desirable to constrain the cooling process more clearly. It may be probable that the number density of chondrules would be so large that chondrules would collide with each other with slow relative velocities and would easily become compound (Ikeda, 1980; Lux *et al.*, 1981; Gooding and Keil, 1981). Most parts of the condensed dust layer (the central part of the chondrule-forming region) would be affected by such heating processes. There would remain, however, unirradiated material that would later become matrices in ordinary chondrites through the mixing with various parts of the dust layer and planetesimals. It appears reasonable under these circumstances that chondrules occupy more than half and sometimes 70% of the chondrites' volume (Wasson, 1972, 1974; Hutchison *et al.*, 1980). After the events of chondrule formation, the primordial gas would escape and solid material would accumulate to form kilometer-sized planetesimals that became consolidated with the aid of interchondrule matrix materials (Fujii *et al.*, 1981).

It is concluded that the duration of each heating event should be less than 0.01 sec for relict minerals to exist commonly in chondrules. The heating events would be closely spaced so that the cooling of chondrules was governed by the surrounding gas-dust mixture a few kilometers wide. The gas and smaller dust would also be heated by the radiation from lightning and melted chondrules. A wide variety of cooling rates can be interpreted as the cooling time scale of this gas-dust mixture in the evolving planetesimals. As far as these constraints are satisfied, other mechanisms such as a drag heating of infalling dust particles through the nebula (Wood, 1983) could not be precluded. The constraints seem concordant with the "lightning" model, although detailed investigations of other heating mechanisms are obviously needed.

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