HEATING ENERGY INPUT RATE FOR CHONDRULE FORMING REGION AND ITS EVOLUTION. T. Nakamoto\(^1\), N. T. Kita\(^2\), and S. Tachibana\(^3\); \(^1\)Center for Computational Physics, University of Tsukuba, Tsukuba 305-8577, Japan, nakamoto@rcpp.tsukuba.ac.jp; \(^2\)Institute of Geoscience, Geological Survey of Japan, AIST, Tsukuba 305-8567, Japan, noriko.kita@aist.go.jp; \(^3\)Department of Geological Sciences, Arizona State University, P. O. Box 871404, Tempe, AZ 85287-1404, USA, tachi@asu.edu.

**Introduction:** Chondrules are believed to have formed through some sort of heating events in the early solar system. Although several heating mechanisms have been proposed to date, no one has been widely accepted. In this work, we attempt to reveal the gross feature of the heating events, especially the heating energy input rate, which is a product of the energy given to the chondrule-forming system by every heating event and the frequency of the chondrule-forming heating events, and its time variation. The energy input rate can be deduced without specifying any particular heating mechanism by using the fraction of chondrules in chondrites and the age distribution of chondrules as constraints.

Since the age distribution of chondrules is not well-determined, we estimate it first. Then, we make a simple model for chondrule formation and obtain the heating energy input rate as a function of time by comparing model results with observations.

**Age Distribution:** We compiled the \(^{26}\)Al-\(^{26}\)Mg ages of twenty UOC chondrules from type 3.0-3.1 ordinary chondrites [1-4]. We do not include data from UOCs with petrologic sub-types higher than 3.3 because there is a possibility of age resetting by the mild thermal metamorphism [2, 5]. From this data set, we obtain age variation somewhere between 1 m.y. and 3 m.y. (the origin of the time is set to be the formation time of CAI) with a peak near 1.8 m.y., though many data show a large age error of \(> 0.5\) m.y., making it difficult to estimate detailed age distribution. We consider the age distribution, showing a peak at \(\sim 2\) m.y., well represents the general trend among chondrules from LL chondrites, although detail distributions should not be considered seriously.

Mostefouzi and co-workers first indicated that there is a correlation between \(^{26}\)Al-ages of LL3.0-3.1 chondrules and their olivine and pyroxene contents [4]. This is further recognized as a correlation between \(^{26}\)Al-ages and bulk volatile (Si, Mn, Na)/Mg ratios by Tachibana et al. [6], indicating that chondrule bulk chemical compositions changed with time. If we assume this correlation to the whole population of chondrules, we can estimate age distribution by applying bulk Si/Mg distribution of chondrules. Unfortunately, bulk analyses of Si/Mg ratios of LL3.0-3.1 chondrules are limited [e.g., 6, 7]. For this reason, we estimated the range of Si/Mg ratios among six types of chondrules (IA, IAB, IB, IIA, IIAB, IIB) from bulk analyses and multiply it with the frequency of these six types of chondrules [8] to obtain the distribution of Si/Mg ratios. Then, the bulk Si/Mg distribution is converted to the age distribution, as shown in Fig. 1. We can see the peak at 1.8 m.y. as in the case of measured data.

Both the measured chondrule data and the estimated age distribution by using the chondrule type frequency and the age-Si/Mg correlation indicate that the ages of chondrules distribute between 1 m.y. and 3 m.y. with a peak at \(\sim 1.8\) m.y.

**Chondrule Formation Model:** We make a simple model for chondrule formation to examine the chondrule-forming heating energy input rate. We do not specify any heating mechanism here. We assume that all the chondritic material is categorized into two groups, for simplicity: “matrix material;” which includes small dust particles consisting of matrix and large unheated dust aggregates, and “chondrules.” We model the chondrule formation as follows: (1) all the material is in a closed volume where chondrule and chondrite formation/destruction take place, (2) the heating event is local and affects only a minor fraction of material in the volume at one time, but occurs many times during the chondrule formation epoch, (3) a certain fraction of heated “matrix material” (“chondrule”) is converted to “chondrule” (“matrix material”) by the chondrule forming (destructing) heating events, and (4) the age of a chondrule, which is the last heating time of the chondrule, is reset by the heating event. The heating energy input rate is defined, in the model, as the fraction of the material in the volume affected by the heating events in a unit time. When we assume that conversion factors from heated “matrix material” (“chondrule”) to “chondrule” (“matrix material”) are constant during the chondrule formation epoch, the fraction of chondrules among all the material, the fraction of reheated chondrules, and the chondrule age distribution can be obtained as functions of the heating energy input rate and the time.

**Results and Discussion:**

**Total amount of heating:** The model shows that the total amount of heating, which is the time integration of the heating energy input rate over the chondrule formation epoch, should be more than 2 or 3 times the total amount of material to reproduce the observed fraction of chondrules (70% is the adopted value here). This
means that a dust particle is averagely heated more than 2 or 3 times during the heating epoch. Thus, a dust particle is heated about 1 time or more at every $10^6$ yr. Interestingly, this result does not depend on the time variation of the energy input rate.

**Fraction of reheated chondrules:** The fraction of the reheated chondrules among all the chondrules is also obtained as the function of the total amount of heating. It is suggested that about 60 ~ 95% (depending on the conversion factors) of chondrules should have been reheated, which is consistent with the idea of chondrule recycling.

**Age distribution of chondrules:** The age distribution of chondrules is dependent on the time variation of the energy input rate. We used several cases of evolution of the energy input rate (constant, linearly decreasing, sinusoidal with a peak at 2 m.y., and exponential decreasing) to calculate the (last heated) age distribution of chondrules. Obtained distributions are displayed in Fig. 2. It is seen that the exponential decreasing case has a peak between 1.5 and 2 m.y. and the distribution seems to be similar to the estimated distribution shown in Fig. 1. Other cases can reproduce neither a peak younger than 2 m.y. nor the overall distribution. Thus, it seems likely that the energy input rate decreases exponentially with time in the chondrule formation epoch.

**Amount of chondrules at 1 m.y. after CAIs:** The earliest time stamp of chondrules observed so far is ~1 m.y. after CAIs. The model shows that the amount of chondrules at that time would not be zero. This result, along with the time variation of the energy input rate (exponential decrease), suggests that the chondrule-forming heating events may have started before 1 m.y., but the $^{26}$Al-$^{26}$Mg system of those earlier-formed chondrules may have been reset by subsequent heating events.

**Summary:** The age of chondrules in LL chondrites is estimated to be in a range from 1 m.y. to 3 m.y. after the CAI formation time with a peak around at 2 m.y. Our chondrule formation model shows some constraints on chondrule forming events: (1) The average number of heating events experienced by a dust particle is more than two or three. (2) More than a half of the chondrules seen today might have been reheated. (3) The age distribution is well reconstructed by the energy input rate decreasing exponentially with time. (4) The chondrule-forming heating events might have begun earlier than 1 m.y. after CAIs. These constraints will help us elucidate the chondrule forming mechanism.

**References:**


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**Fig. 1.** Estimate of the chondrule age distribution by using a correlation of age and bulk Si/Mg ratio (histogram). The line shows the measured distribution of porphyritic chondrules in LL3.0-3.1 chondrites. Peaks at around 1.8 m.y. are seen in both the estimated and the measured distributions.

**Fig. 2.** Age distributions of chondrules calculated with the chondrule formation model. Four curves correspond to four cases of the energy input rate evolution: constant (case 1), linear decrease (case 2), sinusoidal with a peak at 2 m.y. (case 3), and exponential decrease (case 4). The distribution derived from the exponentially decreasing energy input rate (case 4) is similar to those in Fig. 1 in terms of the peak position and the overall distribution.