A MODEL OF THE ORDINARY CHONDRITE PARENT BODY: AN EXTERNAL HEATING MODEL

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***Abstract*:** By employing the best available constraints including the metamorphic temperature and the volume fraction of the type 6 chondrites in the parent body, we examined the external heating model for the ordinary chondrite parent body and compared the results with those obtained by the internal heating model. The Fourier number ($k\Delta t/R^2$) obtained is about 0.05 for the H-chondrite parent body and about 0.15 for the L-chondrite parent body, respectively. The radius R for the H-chondrite parent body is 2–4 km for $\Delta t \sim 10^5$ yr; 5–10 km for $\Delta t \sim 10^6$ yr, where Δt is the duration of the external heat source. For the L-chondrite parent body, the radius is about 0.6 times as large as that of the L-chondrite parent body. In the external heating model, the parent body of the ordinary chondrite must be small because of the short duration of the possible heat sources. The ordinary chondrite parent body (or bodies) may be the survivals (reheated and crushed afterwards, but not grown) of the planetesimals directly disintegrated from the dust layer in the primordial solar nebula.

1. Introduction

Chemical, petrological or mineralogical studies on the ordinary chondrites have been carried out extensively and the parent body models for the ordinary chondrites have been proposed by many workers (*e.g.* WASSON, 1972, 1974; ANDERS, 1978; MINSTER and ALLÉGRE, 1979; MIYAMOTO, 1979; MIYAMOTO *et al.*, 1980). Oxygen isotope composition data by CLAYTON *et al.* (1976) point toward the existence of two different parent bodies for H and L (LL) groups chondrites. However, there remain many problems unsolved. For example, it has been a subject of controversy whether the chemical fractionations involved in the formation of chondrules and chondrites have occurred in the primordial solar nebula or in parent bodies. Though highly-volatile elements fractionation is closely related to the evidence for (thermal) metamorphism (WASSON, 1974) and it is considered that the thermal metamorphism has produced the entire petrologic types from 3 to 6 in the parent bodies, it is also one of important questions whether the heat source is internal or external. MIYAMOTO (1979) has already examined the case of internal heating in detail and proposed

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the models for the H- and L-chondrite parent bodies heated by the decay energy of ^{26}Al (LEE *et al.*, 1976). Though they answered some of the unsolved problems by this internal heating model, the existence of ^{26}Al as the heat source in the ordinary chondrites has not been confirmed yet.

In this paper, we will examine the external heating model using the similar constraints and parameters to our internal heating model in order to compare the results obtained by the external heating model with those by the internal heating model.

2. Constraints

As briefly pointed out by WASSON (1974) and FUJII *et al.* (1979), possible heat sources for external heating of chondrite parent bodies are as follows: (1) radiant energy flux from a highly luminous Hayashi-phase stage of the sun, (2) heating of the primordial solar nebula by electric currents induced by a highly intense, T-Tauri-type solar wind, and (3) decay energy of the short-lived radionuclides within the primordial solar nebula.

Since the duration of these heat sources is highly model dependent, we consider an initially cold spherical solid body of radius R and temperature T_0, heated from the surrounding primordial solar nebula of temperature T_s (CARSLAW and JAEGER, 1959, p. 233–234). In order to simplify the problem, the temperature distribution $T(r, t)$ is assumed as follows:

$$T(r, t)=T_0,\ t\leqq 0 \text{ for } 0\leqq r\leqq R$$

Table 1. Equilibrium temperatures of type 6 chondrites, estimated by pyroxene geothermometers.

Type		No.	Temperature K		
			Min.	Max.	Mean
H6	(ISHII's[1])	6	1172	1330	1232
	(SAXENA's[2])	7	1058	1263	1148
L6	(ISHII's)	7	1164	1299	1240
	(SAXENA's)	8	1098	1243	1177
	(This study[3])	3	1181	1244	1204
LL6	(ISHII's)	6	1219	1283	1251
	(SAXENA's)	6	1153	1248	1193
	(This study)	1			1218

1: ISHII *et al.*, 1976, 1979.
2: SAXENA, 1976.
3: Estimated by ISHII's pyroxene geothermometer (ISHII *et al.*, 1976). Chemical composition data from NAGAHARA (1979) for Yamato chondrites.

and

$$T(R,t)=\begin{cases} T_s, & 0\leqq t\leqq \Delta t \\ T_0, & t>\Delta t \end{cases} \tag{1}$$

where t and Δt are the time and the duration of the heat source, respectively.

T_s is considered to be the maximum metamorphic temperature of the type 6 chondrites because the type 6 chondrites are located at the surface layer of the parent body in the external heating model. Table 1 shows the metamorphic temperatures of the type 6 chondrites estimated by the pyroxene geothermometers (ISHII *et al.*, 1976, 1979; SAXENA, 1976) together with the results obtained by ISHII's pyroxene geothermometer based on the chemical analysis data for some Yamato chondrites (NAGAHARA, 1979). We adopted 1300 K for T_s. This value is approximately the maximum metamorphic temperature of H6 and L6 chondrites. The range of the metamorphic temperatures of the type 6 chondrites is about 200 K (Table 1). Namely, the minimum value we used of the metamorphic temperature of the type 6 is about 1100 K.

We assumed that the volume fraction of the H6 chondrites in the parent body is about 30% and that of L6, about 70% (Table 2). These values are based on the distribution of the ordinary chondrite falls (WASSON, 1974) and the statistics of the ordinary chondrites found in Antarctica (YANAI, 1979; TAKEDA *et al.*, 1979), assuming that the volume fraction of the type 6 chondrites in the parent body is represented by the abundance of the type 6 among the ordinary chondrite falls (Table 2). T_0 is assumed to be 200 K (MIYAMOTO, 1979).

Table 2. Distribution of chondrites among the petrologic types.

		Type				No.
		3	4	5	6	
H	(WASSON's[1])	5.3%	20.2%	46.5%	28.1%	114
	(Antarctic[2])	5	26	36	33	38
L	(WASSON's)	5.5	6.7	17.0	70.9	165
	(Antarctic)	9	20	15	56	33
LL	(WASSON's)	17.6	2.9	20.6	58.8	34

1: Ordinary chondrite falls (WASSON, 1974).
2: Distribution of chondrites in Antarctic meteorite collection (YANAI, 1979; TAKEDA *et al.*, 1979).

Thermal diffusivity of the ordinary chondrite parent body is assumed uniform and the range of values ($1\text{–}5\times10^{-3}$ cm^2/s) is referred from MATSUI and OSAKO (1979), in which these are measured for various chemical- and petrologic-type ordinary chondrites found in Antarctica.

3. Results

We first consider the maximum attainable temperature (T_{max}) within the parent body by the externally heated condition (eq. (1)). Fig. 1 shows relative temperature T_{max}/T_s as a function of relative radius r/R with the Fourier number ($k\, \Delta t/R$) as a parameter, in which k and Δt are the thermal diffusivity of composing material and the duration of heat source, respectively. On the basis of the volume fraction of the type 6 chondrite in the parent body and the metamorphic temperature range (1300 K—*ca.* 1100 K) of the type 6 chondrites, the value of Fourier number is to be about 0.05 for the H-chondrite parent body as shown in Fig. 1. The value of Fourier number for the L-chondrite parent body is about 0.15.

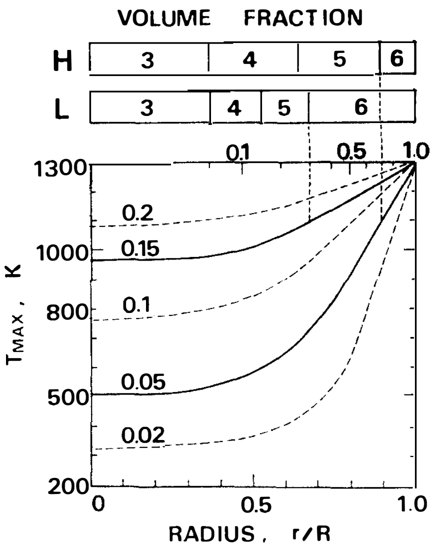

Fig. 1. Relative temperature versus radius with the Fourier number ($k\, \Delta t/R^2$) as a parameter. At top of the figure, volume fractions among petrologic types for both H and L chondrites are also shown with modified scale to fit the linear radius scale.

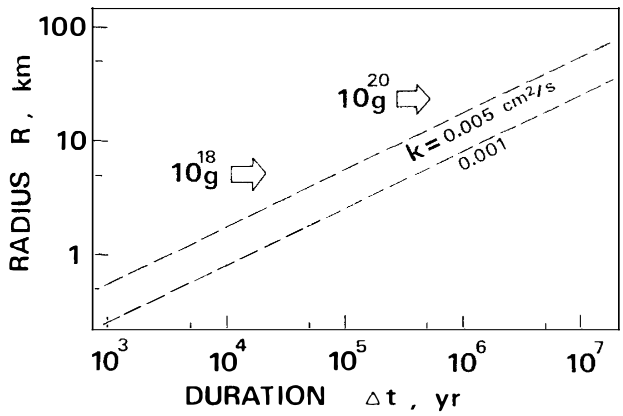

Fig. 2. Radius of a parent body versus duration in the case of the Fourier number of 0.05 and the values of thermal diffusivity to be 5×10^{-3} cm²/s and 1×10^{-3} cm²/s.

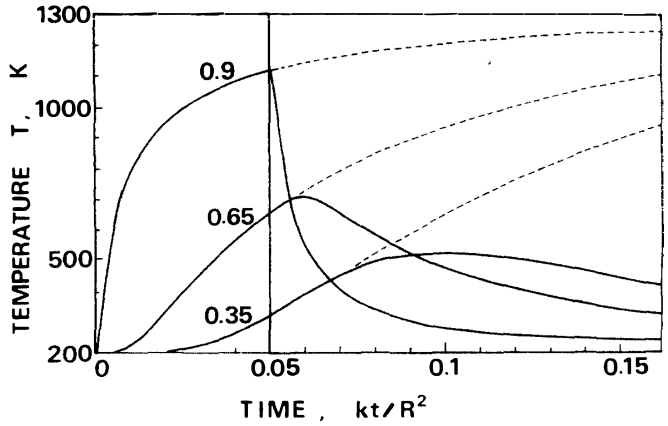

Fig. 3. Temperature variations with elapsed time (kt/R^2) for three radii (r/R) of H-chondrite parent body in the case of the Fourier number of 0.05. Numbers on curves denote r/R and dotted lines show the temperatures for the case of infinite duration of the heat source ($\Delta t \rightarrow \infty$).

For the constant Fourier number of about 0.05 for the H-chondrite parent body, the radius R of the parent body is related to duration Δt of the external heat source, *i.e.*, the duration of the surrounding temperature of 1300 K (Fig. 3). In Fig. 3, temperature variations with relative radius (r/R) as a parameter are shown as a function of elapsed time (kt/R^2) for the constant Fourier number of 0.05. From Figs. 2 and 3, for $\Delta t \sim 10^5$ yr, then R=2–4 km, or $\Delta t \sim 10^6$ yr then R=5–10 km are concluded using probable thermal diffusivity ranges of $(1\text{–}5)\times 10^{-3}$ cm^2/s after MATSUI and OSAKO (1979).

For the L-chondrite parent body with the constant Fourier number of 0.15, a probable radius is about 0.6 times as large as that of the H-chondrite parent body.

4. Discussions

At the early stage of the accretion of chondrite parent body (or bodies), a primordial dust layer disintegrated into a large number of planetesimals with masses of about 10^{18} g or radii of a few km (SAFRONOV, 1969; GOLDREICH and WARD, 1973). On the external heating model, the parent body of the ordinary chondrite must be relatively small because of the short duration of the possible heat sources. WASSON (1972) concluded that the radius of parent body should be some tens of meters because the duration of the most probable external heat source (the Hayashi-phase of the sun) was about 10^3 yr. According to our results, if the duration of the external heat source, *i.e.*, the duration of 1300 K at the surface, is 10^5–10^6 yr, the radius of the parent body estimated above is about 2–10 km. If this is the case, it is intensely interesting to note that the ordinary chondrites' parent body may be the survival (reheated and crushed afterwards, but not grown) of these planetesimals directly disintegrated from a primordial dust layer.

MIYAMOTO (1979) and MIYAMOTO *et al.* (1980) examined in detail the internal heating model for the ordinary chondrite parent body under the best available constrains which are similar to this external heating model, by assuming that the decay energy of ^{26}Al was the heat source in the parent body. They concluded as follows: (1) The radius of the parent body is 85 km for both H and L chondrites. (2) The ambient temperature of the L-chondrite parent body must be lower than that of the H chondrite. (3) The volume fraction of each petrologic type in the parent body agrees with the distribution of the ordinary chondrite falls among the petrologic types. (4) The maximum attainable temperature at the center of the L-chondrite parent body is higher than that of the H chondrite because of its higher Al bulk content than H's. (5) The contradiction that the cooling rate of the type 3 chondrite estimated from Fe-Ni data is slower than that of the type 6 can be explained even in the case of the internal heating model.

Contrary to the internal heating model, the radius of the parent body can not precisely be determined, but is sensitively dependent on the duration of the heat source and thermal diffusivity of ordinary chondrites in the case of the external heating model. The duration of the possible heat sources for the external heating model is so short that the radius of the parent body must be small. Therefore, taking into account the abundances of the ordinary chondrite falls, it is considered that some parent bodies which had the similar small size and have experienced the similar thermal history existed. This fact is in line with our speculation that the ordinary chondrite parent bodies are the products at the stage of the planetesimal formation in the evolution of the primordial solar nebula. Because of a large volume fraction (70%) for the L6 chondrites, the maximum metamorphic temperature for the L3 chondrites would be as high as 950 K whereas that for the H3 chondrites is about 500 K (Fig. 1). Therefore, the investigations to estimate the maximum metamorphic temperature attained for both H3 and L3 chondrites could test whether the external heating model for the ordinary chondrite parent body would be valid or not. If T_0 is assumed to be 100 K (SAFRONOV, 1969), this argument is not affected so much.

As discussed by many authors (*e.g.* WASSON, 1974) for the external heating model, Rb-Sr ages are expected to be nearly the same among the petrologic types (Fig. 3). In the internal heating model, the Rb-Sr age of the type 3 ordinary chondrite is older than that of the type 6 (MIYAMOTO, 1979). The observed cooling rates for the type 3 and type 6 chondrites based on the Fe-Ni data (WOOD, 1967) can easily be explained by the external heating model. The distributions of the ordinary chondrite falls among the petrologic types can be explained by the external heating model as well as the internal heating one (MIYAMOTO, 1979), assuming that the distributions among the petrologic types are represented by the volume fractions in the parent body (Fig. 1).

The results of the external heating model depend almost entirely on the duration and extent of external temperature, that is, thermal evolution of the primordial solar nebula. Because the duration of a luminous Hayashi-phase of the sun appears to be too short to reheat km-size parent bodies (WASSON, 1974), the probable external heat sources are T-Tauri-type solar wind or the decay energy of ^{26}Al in the (dense) primordial solar nebula. Although the heating mechanisms of the primordial solar nebula by these heat sources are not well known, the duration Δt could be 10^5–10^6 yr. The heating mechanisms of the primordial solar nebula must be examined in more detail, because the temperature of the primordial solar nebula (in terms of the distance from the proto-sun) plays an important role even in the internal heating model (MIYAMOTO, 1979).

It is necessary to carry out the chemical or petrological examination of the type 3 ordinary chondrites in more detail. The location of the type 3 chondrite is a determining factor for the model of the ordinary chondrite parent body. It is also important to search for the evidence of the presence of ^{26}Al in ordinary chondrites in order to determine whether the heat source is internal or external.

In conclusion, whatever the heat source may be, the size of the parent body (or bodies) of the ordinary chondrites is relatively small. This conclusion is in line with the hypothesis that Apollo asteroids are the source of the ordinary chondrites.

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