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THE CORRELATION OF CHONDRULE TEXTURE AND MAGNESIUM ISOTOPE ABUNDANCE IN ALLENDE METEORITE

Chiaki UYEDA, Mari SUZUKI and Jun OKANO

College of General Education, Osaka University, 1–1, Machikaneyama-cho, Toyonaka 560

Abstract: The Mg isotope abundance of the individual chondrules in the Allende meteorite was measured by ion microprobe mass analysis. The amounts of ^{24}Mg excess with respect to the terrestrial fractionation line were obtained for each chondrule. Barred olivine and glassy chondrules tend to have relatively large ^{24}Mg excess, whereas porphyritic and radial pyroxene chondrules have relatively small ^{24}Mg excess. The following three factors were taken into consideration in connection with the formation process of these chondrules in the Allende meteorite; (1) the temperature conditions at the formation of the chondrules, (2) the relative abundance of each chondrule type, (3) the amount of ^{24}Mg excess in each chondrule type. It is shown that chondrules formed at high temperature or by rapid cooling have relatively large ^{24}Mg excess and their relative abundance is small, whereas chondrules formed at low temperature or by slow cooling tend to have small ^{24}Mg excess and their relative abundance is large. A model of chondrule formation process in the early solar nebula is proposed to explain the relations between factors (1)–(3).

1. Introduction

Since the discovery of ^{16}O anomaly reported by CLAYTON *et al.* (1973), many works have been done on ^{16}O, ^{26}Mg and other isotope anomalies in primitive meteorites (CLAYTON *et al.*, 1973; LEE *et al.*, 1976). The results on these isotope anomalies indicate that the solar nebula was isotopically inhomogeneous and composed of at least two components. Most of the isotope anomalies have been found in particular types of inclusions such as CAI in the Allende meteorite.

NISHIMURA and OKANO (1982, 1984), NISHIMURA *et al.* (1985) and OKANO and NISHIMURA (1986) reported previously the excess of ^{24}Mg relative to the mass fractionation line (m.f.l.) of terrestrial magnesium, in primitive Antarctic meteorites such as ALH-77216 (L3), ALH-763 (LL3) and Y790992 (C3) and in the Allende meteorite (C3). The excess was widely found in a number of chondrules and also in the matrix. However, most of the measurements have been carried out on Al-poor and Mg-rich areas without clear identifications of chondrule types. It is expected that the correlation between chondrule textures and the ^{24}Mg excess will give an important key to investigate not only the injection mechanism of ^{24}Mg-rich material into the chondrules but also the mechanism of chondrule formation. Therefore, the isotope abundance measurements of Mg are carried out for the texture-identified chondrules of the Allende meteorite in the present work.

2. Experimental Procedure

Sixteen chondrules of the Allende meteorite are measured in this work. The sample preparation was carried out in the following way: A meteorite sample of Allende was cut with a wire saw of 0.12 mm in diameter. From one side of the cut surface, a thin section specimen for a polarizing microscope is prepared. The other side of the cut surface is polished and used for magnesium isotope abundance measurements. The texture of chondrules on the sample surface is identified from the corresponding optical image of the thin section.

A modified Hitachi IMA-2A ion microprobe analyser was used for the measurement of the magnesium isotope abundance. The primary ions were 9 keV O_2^+ ions with a beam current of about 1 μA. The spot size was 80–120 μm in diameter. The Mg isotope measurements were carried out for 8 to 20 spots on each chondrule section. Details in the ion microprobe analysis have been shown elsewhere (NISHIMURA, 1982; NISHIMURA and OKANO, 1982).

Since the mass resolution of Hitachi IMA-2A was about 300, special care has been taken for the interference with the isotopic peaks due to multiply-charged ions and molecular ions. Detailed discussions of the interference was described in the previous papers (NISHIMURA, 1982; NISHIMURA *et al.*, 1985; SAKAGUCHI *et al.*, 1988). A number of ionic species which may interfere with the isotopic abundance measurement has been examined for every measured spot of the meteorite. Especially, contributions of $^{23}NaH^+$, $^{24}MgH^+$ and $^{12}C_2^+$ to the Mg isotope peaks were carefully checked. The intensities of $^{23}Na^+$ and $^{12}C^+$ were small for all the measured spots and the contribution of $^{23}Na^+$ and $^{12}C^+$ to the mass 24 peak was estimated to be negligibly small ($^{23}NaH^+/^{24}Mg^+ < 3\times10^{-6}$, $^{12}C_2^+/^{24}Mg^+ < 6\times10^{-6}$). Only serious interference came from $^{24}MgH^+$. When a new sample of the meteorite is mounted on the sample holder, the contribution of $^{24}MgH^+$ to the mass 25 peak was large at the beginning, but after a few days it decreased to the negligible level ($^{24}MgH^+/^{25}Mg^+ < 10^{-3}$). It is noticed that the use of the cold finger placed near the sample was effective to decrease the contribution of interfering ions quickly.

3. Results and Discussion

The chondrule samples measured in the present work are listed in Table 1. They are five porphyritic (P), three radial pyroxene (R), six barred olivine (B) and two glassy (G) chondrules.

The values of $\Delta(24/25)$ and $\Delta(26/25)$ are calculated for each spot, where $\Delta(24/25)$ and $\Delta(26/25)$ are given by the following relation;

$$\Delta(m/25) = \{({}^{m}Mg/{}^{25}Mg)_{sample}/({}^{m}Mg/{}^{25}Mg)_{s.t.d} - 1\} \times 1000(‰) \quad (1)$$

$$m = 24, 26$$

where the subscripts "s.t.d" mean the natural isotope abundance ratios reported by

Table 1. List of chondrule samples measured in the present work. The mean values of measured Δ(24/25) and Δ(26/25) for each chondrule are also shown. Δ(m/25) is defined in equation (1). Δ24 is defined in equation (2). σ_m is given in the parenthses.

	Symbol	Δ(24/25) (‰)	Δ(26/25) (‰)	Δ24 (‰)	Average Δ(24/25) (‰)	Average Δ(26/25) (‰)
Porphyritic	P1	15.1(0.4)	− 7.2(0.3)	7.9		
	P2	17.8(0.8)	− 9.7(0.7)	8.1		
	P3	18.6(0.5)	− 8.4(0.9)	10.2	18.2(1.0)	−8.5(0.5)
	P4	18.9(1.2)	− 9.5(0.5)	9.4		
	P5	20.5(1.5)	− 7.9(1.0)	12.6		
Radial pyroxene	R1	12.3(0.5)	− 6.9(0.4)	5.4		
	R2	15.8(0.8)	− 7.4(0.7)	8.4	15.7(1.9)	−8.6(1.5)
	R3	18.9(1.8)	−11.4(1.2)	7.5		
Barred olivine	B1	19.8(0.4)	− 9.7(1.8)	10.0		
	B2	16.8(0.4)	− 6.2(0.5)	10.6		
	B3	21.6(0.8)	− 8.9(0.6)	12.7	20.4(1.2)	−10.0(1.0)
	B5	17.8(0.6)	−11.2(0.8)	6.6		
	B6	24.2(1.7)	−13.1(0.8)	11.1		
	B7	22.0(0.7)	−10.6(1.2)	11.4		
Glassy	G1	22.8(1.4)	−12.6(0.9)	10.2		
	G2	20.2(0.8)	− 8.4(0.6)	11.8	21.5(1.3)	−10.5(2.1)

Table 2. Δ(24/25) and Δ(26/25) of all the spots measured on P2, B7, R2 and G1 chondrules.

P2 Spot No.	Δ(24/25)	Δ(26/25)	B7 Spot No.	Δ(24/25)	Δ(26/25)	R2 Spot No.	Δ(24/25)	Δ(26/25)	G1 Spot No.	Δ(24/25)	Δ(26/25)
1	19.9	−16.2	1	24.5	−13.8	1	18.3	−2.3	1	28.8	−11.9
2	13.4	−12.9	2	23.2	−12.3	2	14.9	− 6.9	2	24.8	−13.2
3	19.6	− 8.1	3	20.3	−10.0	3	13.9	− 8.2	3	16.3	−18.0
4	16.7	− 7.2	4	21.5	− 9.7	4	12.2	− 7.6	4	21.8	−11.6
5	17.2	− 8.7	5	18.9	−11.2	5	14.4	− 6.7	5	19.6	−11.2
6	19.0	− 9.2	6	24.9	− 4.1	6	13.0	−10.2	6	28.4	−10.3
7	19.7	− 9.1	7	21.1	− 9.6	7	15.1	− 7.6	7	19.6	−10.0
8	16.8	−10.4	8	21.6	−10.3	8	19.2	−12.0	8	20.8	−15.4
9	21.4	− 6.9				9	15.4	− 8.2	9	25.3	−12.0
10	22.5	− 6.9	$\overline{m}$	22.0	−10.6	10	16.1	− 6.1			
11	14.6	−10.7	σ_m	0.7	1.2	11	20.9	− 6.1	$\overline{m}$	22.8	−12.6
12	16.1	−10.2	σ	2.0	2.8				σ_m	1.4	0.9
13	15.4	−10.2				$\overline{m}$	15.8	− 7.4	σ	4.3	2.6
						σ_m	0.8	0.7			
$\overline{m}$	17.8	− 9.7				σ	2.6	2.3			
σ_m	0.8	0.7									
σ	2.7	2.6									

CATANZARO *et al.* (1966), $(^{24}Mg/^{25}Mg)_{s.t.d}=7.89702$, $(^{26}Mg/^{25}Mg)_{s.t.d}=1.1002$. Table 2 shows the results of the measured spots for P2, R2, B7 and G1 chondrules, which are presented as examples from types P, R, B and G, respectively. The $\Delta(m/25)$ value of each spot is obtained by averaging the results of 20 to 30 mass scannings with $2\sigma_{mean}<3‰$. $\overline{m}$ is the mean value of the $\Delta(m/25)$ values for all the measured spots on the respective chondrules, and is adopted as the $\Delta(m/25)$ values of the chondrule. This $\Delta(m/25)$ value of each chondrule is listed in Table 1.

There are two origins which cause the scattering of the data in a single chondrule. One is the instrumental origin. We assess the scattering due to the instrumental origin through the measurements for the terrestrial forsterite sample collected in Ehime Prefecture, Japan. We have used this sample as a laboratory standard. The standard sample is composed of olivine and considered to be much homogeneous compared with meteorite samples. The scattering of the data for the laboratory standard is relatively small for a single run and the $2\sigma_m$ is usually less than $\pm 2‰$. However, taking the reproductivity for different runs and long-term deviations into considerations, the scattering is somewhat large along m.f.l. which amounts to $2\sigma_m \sim \pm 3‰$. Another origin of the scattering of data in a single chondrule comes from the mineralogical complexity of the chondrules. Since most of the chondrules measured here are composed of various kinds of small pyroxene and olivine components, the isotopic ratios may show a relatively large scattering due to the difference in isotopic ratios of each components. The rapid cooling in the chondrule formation process may also cause isotopical inhomogeneity. The scattering of the data in a single chondrule is caused by these two origins.

The $\Delta(24/25)$ and $\Delta(26/25)$ values of each chondrule are compared with those of several terrestrial samples in Fig. 1(a), (b) and (c). In each figure, the solid lines with a gradient of -1 represent m.f.l for terrestrial Mg, and the large open circle shows the mean value of the laboratory standard forsterite. Figure 1(a) shows the measurement results of terrestrial olivine and pyroxene samples. The deviation for these samples with respect to m.f.l is less than $\pm 3‰$. The data are also distributed along m.f.l in a range of about 6‰. This distribution is partly due to the variation of the isotope ratios of each mineral and also due to the experimental mass discrimination. Figure 1(b) shows the results of porphyritic and radial pyroxene chondrules. Figure 1(c) shows the results for barred olivine and glassy chondrules.

The isotope data of Fig. 1(a), (b) and (c) are plotted together in Fig. 2(a). White and black symbols are data of chondrules and terrestrial minerals, respectively. The dash-dotted line with a gradient of -0.34 (line A) is calculated from the chondrule data with the method of least squares. The distribution of chondrule data with respect to terrestrial samples can be interpreted as a results of overlapping of two processes. One of the processes is due to the mass fractionation which distributes the data points in the direction of gradient -1 and the other is a process of unknown origin which distributes the data in the direction of line A. The isotope ratios of chondrules show distribution in the -1 direction in the range of about several permils, which is comparable to that of terrestrial samples. The variety of the mineral compositions of the chondrules measured here, which ranged from olivine-rich to pyroxene-rich compositions, may have caused the distribution along -1 direction. While the

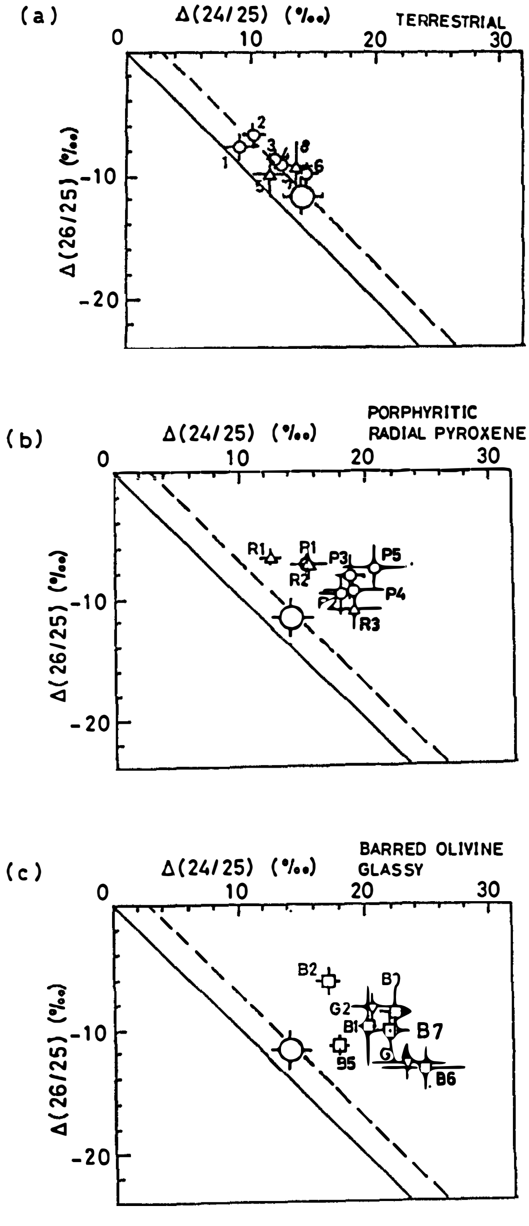

Fig. 1. Three isotope plots of Mg for several terrestrial samples and sixteen Allende chondrules. Solid line shows m.f.l. according to the natural isotope abundance by CATANZARO *(1966). Broken line shows m.f.l. according to the natural isotope abundance by* SCHRAMM *(1970). Large open circles show the mean value of the laboratory standard forsterite (collected in Ehime Prefecture, Japan). The error bars represent* σ_m. *(a) Results of terrestrial samples. 1,2; olivines, Hawaii, 3,4; olivine, Oki, Japan, 5; enstatite, Bamble, Norway, 6; olivine, Hokkaido, Japan, 7; augite, Muroto, Japan, 8; hypersthene, Quebec, Canada. (b) Porphyritic and radial pyroxene chondrules of the Allende metorite. (c) Barred olivine and glassy chondrules of the Allende meteorite.*

distribution along this direction is within the range of several permils, the dominant deviation is seen in the line A direction. The process along the line A direction can be explained by the mixing of a ^{24}Mg-rich material to the terrestrial material. The isotope ratio of the assumed ^{24}Mg-rich material is located somewhere on the exten-

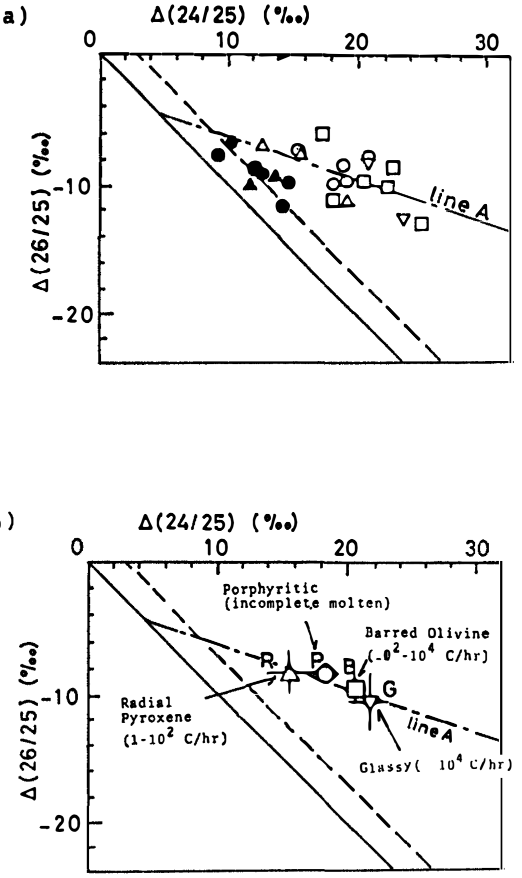

Fig. 2. (a) Distribution of Mg isotope ratios of chondrules of the Allende meteorite (white symbols). ○, △, □ and ▽ are porphyritic, radial pyroxene, barred olivine and glassy chondrules, respectively. The data of terrestrial minerals are shown by black symbols. All the data points of Fig. 1 (a), (b) and (c) are plotted here. The broken line (line A) is calculated from the chondrule data with the method of least squares. (b) The relation between measured Mg isotope ratios and estimated heating conditions of chondrule textures. The temperatures noted in the parentheses are the cooling velocity of each texture estimated from reproduction experiment (TSUCHIYAMA et al., 1980).

tion of line A. The Mg isotope ratios of type 3 meteorites measured previously by NISHIMURA and OKANO (1982, 1984) and OKANO and NISHIMURA (1986) seem to be distributed also along line A, although the scattering of the data points is larger and the tendency is more unclear.

The mixing of ^{26}Mg excess component into the terrestrial mineral can also deviate the chondrule data with respect to m.f.l. It was reported by LEE *et al.* (1976) that the amount of ^{26}Mg excess showed a linear correlation with the Al/Mg ratio in certain types of Al-rich inclusions such as CAI in the Allende meteorite. This correlation was explained consistently by assuming that the excess ^{26}Mg were due to the *in situ* decay of ^{26}Al. The Al/Mg atomic ratios of these inclusions were always larger than 300. However, the Al/Mg ratios of chondrules measured in the present work were always less than 0.3 and no correlation is seen between the amount of ^{26}Mg excess and the Al/Mg ratios. It is difficult to explain the present case in terms of the *in situ* decay of ^{26}Al hypothesis mentioned above. Of course it is possible to assume the mixing of excess ^{26}Mg produced from some other unknown origin to explain the present case. However, one must also assume a large amount of fractionation along m.f.l. in order to explain the distribution of chondrule data with respect to the terrestrial samples. The maximum amount of this fractionation will be about 13‰ which is considerably larger than the distribution mentioned in Fig. 1(a). A complicated mechanism will be needed to explain such process. The mixing of ^{24}Mg-rich material seems to be the most simple explanation for the distribution of chondrule data.

It is seen in Fig. 2(a) that barred olivine and glassy chondrules tend to have larger amount of ^{24}Mg excess compared to those of porphyritic and radial pyroxene chondrules. This is also shown in Table 1 by $\Delta 24$ values,

$$\Delta 24=\Delta(24/25)-\{\Delta(26/25)\times(-1)\}=\Delta(24/25)+\Delta(26/25)\,. \qquad (2)$$

$\Delta 24$ gives the deviation of $\Delta(24/25)$ with respect to m.f.l. in the horizontal direction in the three isotope plots. This gives the amount of ^{24}Mg excess under the assumption that the deviation of data from m.f.l. is completely due to excess of ^{24}Mg. It is seen that glassy and barred olivine chondrules tend to have large $\Delta 24$ values compared to those of porphyritic and radial pyroxene chondrules. The mass fractionation along the -1 direction does not affect the $\Delta 24$ values.

It is interesting to compare the estimated conditions of chondrule formation for each texture type obtained by laboratory experiments with the amount of ^{24}Mg excess. According to the reproductive experiment reported by TSUCHIYAMA *et al.* (1980), chondrules can be formed from completely and incompletely molten precursors, and their textures depend on the cooling velocity V_c and the maximum heating temperature T_{max}. For example, when T_{max} is fixed just above the liquidus temperature (T_l) of the precursor, the glassy, barred olivine and radial pyroxene chondrules can be produced from completely molten liquid state with cooling velocity of more than 10^4°C/h, 10^4–10^2°C/h and 10^2–1°C/h, respectively. On fixing V_c at an order of 10^3°C/h for the same precursors, glassy and barred olivine chondrules appear when the maximum heating temperature is $T_{max}>1550$°C and $1550°C>T_{max}>T_l$, respectively. When $T_{max}<T_l$, the porphyritic chondrules are produced from incompletely molten precursors. This texture is considered to have suffered a relatively moderate heating effect compared with those of other textures. It is seen that chondrules which suffered relatively intense heating such as the glassy and barred olivine chondrules tend to have large ^{24}Mg excess, whereas chondrules formed under moderate heating conditions such as radial pyroxenes and porphyritic chondrules have small ^{24}Mg excess. The relation of heating conditions and isotope ratios of chondrule textures is described in Fig. 2(b). The isotope ratios of chondrule textures are represented by the average values shown in Table 1. The error bars show σ_m.

It is noticed that in general, a majority of chondrules in a chondrite are porphyritic chondrules. NAGAHARA (1983) reported that the relative abundance of chondrules with different textures in the ordinary chondrites is; 80% for porphyritic, 7% for barred olivine, 10% for radial pyroxene and 2% for glassy chondrules. Considering this fact together with heating conditions of the reproductive experiments for the chondrule textures, it is seen that a majority of chondrule precursors suffered a relatively moderate heating and cooling, and formed porphyritic textures. The precursors of barred olivine and glassy chondrules which suffered an intense heating and rapid cooling had relatively small abundance.

In summary, correlations are seen among the following three factors concerned with the chondrules of the Allende meteorite;

(1) the temperature conditions on the formation process of each chondrule type (V_c, T_{max}),

(2) the relative abundance of each texture type (N_A),

(3) the amount of ^{24}Mg excess in each texture type ($\Delta 24$).

4. A Model for Chondrule Formation

One possibile explanation of the above correlation is to assume a free fall of an extra solar-nebula with ^{24}Mg-rich component on the primitive solar nebula. Chondrules can be produced by heating due to the shock wave which is induced by the collision between the extra solar-nebula gas and the solar-nebula gas (HASEGAWA,

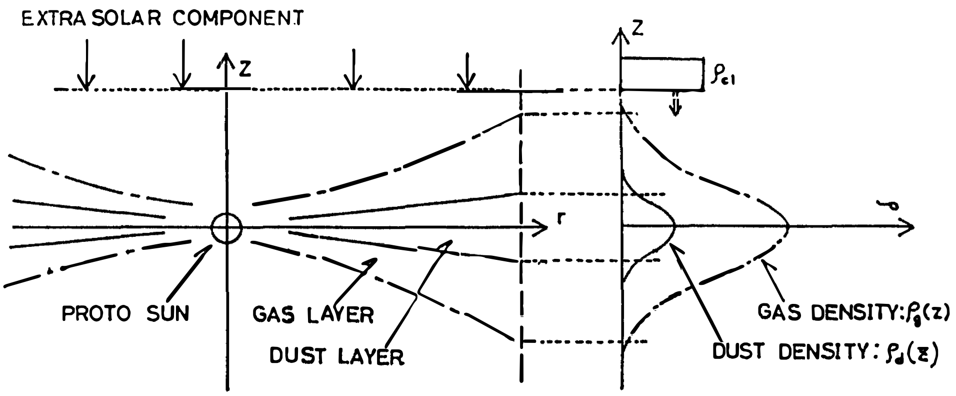

Fig. 3. Schematic view of a chondrule formation model assuming a free fall of an extra solar nebula on the primitive solar nebula. Density distribution of gas and dust along the z-axis is shown in the right portion. ρ_{cl} and ρ_g denote the gas density of free-falling nebula and solar nebula, respectively.

Table 3. Classification of chondrule formation area.

Formation area	Conditions for formation	Formed chondrules
(a) Surface of gas Layer	→(E) contamination: large	
Gas density $\rho(z)$: low	→cooling rate: fast heating temperature: high	glassy chondrules
Dust density: low	→relative abundance: small	barred olivine chondrules
(b) Equatorial plane	→(E) contamination: small	
Gas density: $\rho(z)$: high	→cooling rate: slow heating temperature: low	radial pyroxene chondrules
Dust density: high	→relative abundance: large	porphyritic chondrules

* (E) is the ^{24}Mg-rich extra solar component assumed in § 3.

pers. commun). The extra solar-nebula is assumed to fall on the solar nebula during the period when a gas layer and a dust layer were formed on the equatorial plane (HAYASHI, 1981). The situation is shown in the left part of Fig. 3. The submillimeter size grains in the dust layer are assumed as the precursors of chondrules in this model. The heating temperature T_m of the solar nebula gas phase due to the shock wave heating generally depends on the density ratio of the two gas phases, and T_m will increase with the ratio ρ_{c1}/ρ_g, where ρ_{c1} and ρ_g are the gas density of free-falling nebula and solar nebula, respectively. A preliminary calculation done by HASEGAWA indicates that T_m was around 2000 K at $r=1$ AU and $\rho_{c1}/\rho_g=0.1$, where r is the distance from the protosun. In this calculation, T_m was assumed, for simplification, to be constant along the z-axis which is the axis perpendicular to the equatorial plane.

We extend the above shock wave heating model by HASEGAWA, taking the z-dependence of T_m into consideration. Actually, T_m will increase with z, since the z-dependence of ρ_g is derived to be $\rho_g(r, z)=\rho_0 r^{-t} \exp\{-z^2/z_0(r)\}$ where $z_0(r)$ is the half thickness of the nebula with numerical fitting constant $t=2.75$ and $\rho_0=1.4\times 10^{-9}$ gcm^{-3} (HAYASHI, 1981). The cooling velocity of the precursor also increases with z because the radiation of heat from the precursors is less suppressed as the gas density $\rho_g(z)$ decreases. This means that the chondrule precursors near the equatorial plane suffer a relatively moderate heating and slow cooling process, while precursors far apart from the equatorial plane suffer a relatively intense heating and rapid cooling process. Comparing these z-dependent temperature conditions with the experimentally determined temperature conditions of chondrule formation for each texture type, the formation area of chondrule textures can be classified tentatively along the z-axis (Table 3). That is, porphyritic chondrules are formed near the equatorial plane, while glassy and barred olivine are formed in an area far away from the equatorial plane.

The relative abundance of chondrule textures N_A depends on the dust density $\rho_d(z)$, since the chondrule precursor is assumed to be the submillimeter-sized grains formed in the dust layer. Up to now there is no quantitative discussion on the z-dependence of dust density. However, for a qualitative discussion, one can assume that $\rho_d(z)$ takes the maximum value at $z=0$ and decreases with $|z|$ as shown in Fig. 3. Therefore, it is expected that most of the chondrules are formed near the equatorial plane and the population of chondrules decreases with z.

In the present model, we assume that the ^{24}Mg excess component was brought by the extra solar nebula gas. The injection of extra ^{24}Mg into individual chondrules is assumed to be caused by the exchange of magnesium between the heated precursor and the surrounding gas phase. Since the gas phase is a mixture of extra solar and solar components, the amount of ^{24}Mg excess of the gas phase increases with $\rho_{c1}/(\rho_{c1}+\rho_g(z))$ and hence with z. This means that ^{24}Mg excess of the chondrules is relatively small near the equatorial plane and increases with z.

There is no effective evidence so far to estimate the origin of the ^{24}Mg excess component in the above model. One explanation for producing ^{24}Mg-rich component is the event of neutron-poor explosive carbon burning in a supernova explosion proposed by ARNETT (1969), which has been applied to explain the origin of ^{16}O anomalies (CLAYTON *et al.*, 1973). If the ^{24}Mg excess material and the ^{16}O excess material both formed in the same nucleosynthetic event, and injected into the primitive solar nebula, we can expect some correlation between the two kinds of anomalies in meteorites. However, judging from the reported data so far, no positive correlation is seen between them. An explanation for this fact is that the ^{24}Mg excess material and the ^{16}O excess material may have formed from different nucleosynthetic events. According to the recent theory of star formations, it seems possible that the solar nebula encountered with supernova remnants several times at different stages of its evolution (REEVES, 1978).

From the above model of chondrule formation, barred olivine and glassy chondrules have relatively a large amount of ^{24}Mg excess and a small amount of N_A, compared to porphyritic and radial pyroxene chondrules. It is seen that the model presented above gives a qualitatively sufficient explanation for the observed tendency of the three factors; (1), (2) and (3) discussed in section 3.

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