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CONDITION FOR THE FORMATION OF THE COMPOUND CHONDRULES IN THE SOLAR NEBULA

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Abstract: The conditions for compound chondrule formation described by J. L. GOODING and K. KEIL (Meteoritics, **16**, 17, 1981) are reexamined using the criterion of gravitational instabilities (M. SEKIYA, Prog. Theor. Phys., **69**, 1116, 1983). If a compound chondrule was formed by collisional sticking of a plastic particle with a solid or another plastic particle, the following conclusions are derived: (1) Chondrules were formed after the settling of dust particles had progressed and the number density of dust particles had increased by several orders of magnitude. (2) To reproduce the observed ratio of the compound chondrules to all the chondrules, collisional velocities of pre-chondrule particles must have been larger than about 1.6 m s^{-1}, and the Weber number for the collision of molten pre-chondrule particles must have been larger than about 40, if we assume that the chondrule formation occurred in the asteroid region in the stage where dust particles were floating in the solar nebula. In this case, collisional sticking would be difficult. If sticking is impossible, then other formation mechanisms for the compound chondrules must be considered (*e.g.* J.T. WASSON *et al.*, Geochim. Cosmochim. Acta, **59**, 1847, 1995). (3) If chondrules were formed in the inner regions of the solar nebula, the lower limits for the relative velocities of the pre-chondrule particles would be reduced.

1. Introduction

The standard scenario for the formation of the planetary system is as follows (SAFRONOV, 1969; HAYASHI *et al.*, 1985):

(1) The Sun and the solar nebula were formed after the collapse of a molecular cloud core.

(2) Solid dust particles stuck to each other by mutual collisions and settled towards the midplane of the solar nebula.

(3) A thin dust layer fragmented due to gravitational instabilities and planetesimals with radii on the order of 10 km were formed.

(4) The terrestrial planets and cores of the giant planets were formed by collisional coagulation of planetesimals.

In which stage of the above scenario were the chondrules formed? Do we need to construct another story of the solar system formation to be consistent with the formation of the chondrules? To answer these questions, we consider a necessary condition for the formation of the compound chondrules. We make the simplifying assumption that the compound chondrules were formed by mutual collisions of pre-chondrule particles whose temperatures were high enough to be partially melted. We then estimate the number densities and velocities of the particles necessary to reproduce the observed ratio of the compound chondrules to all the chondrules. This type of calculation was first made by GOODING and KEIL (1981). Following their analysis, and considering the scenario of the solar system formation, we then estimate the condition for the formation of the compound chondrules.

2. Observed Ratio of the Compound Chondrules

The ratio of the compound chondrules was determined by microscopic observation of thin sections of 50 unequilibrated ordinary and carbonaceous chondrites from Antarctica (detailed results are presented in the Appendix). 65 compound chondrules were identified through the inspection of ~6500 chondrules; including 14 enclosing, 29 adhering and 22 consorting types based on the classification of compound chondrules proposed by WASSON (1993). Thus, the ratio of the compound chondrules to all the chondrules is around 1×10^{-2}. All chondrite types (H, L, LL and C) show a similar ratio of compound chondrules. Since this ratio is obtained by observation of thin sections, the real percentage should be larger. Thus we assume a value of 3×10^{-2} as being representative in the early solar nebula at the time of chondrule formation. These results are consistent with those by GOODING and KEIL (1981), and WASSON *et al.* (1995).

3. Condition for the Formation of the Compound Chondrules

We have considered a necessary condition for the formation of compound chondrules using the model by GOODING and KEIL (1981). We do not specify mechanisms of chondrule formation, which might be heating by lightning (WHIPPLE, 1966; HORÁNYI *et al.*, 1995), gas drag (HOOD and HORÁNYI, 1991, 1993), or magnetic reconnection (SONETT, 1979; LEVY and ARAKI, 1989) in the solar nebula. We only use the observations that the chondrules have the following characteristics:

(a) the typical radius is $a=10^{-1}$ cm,

(b) the typical cooling time was on the order of $\Delta t=10^3$ s (TSUCHIYAMA *et al.*, 1980, 1981),

(c) the ratio of compound chondrules to all the chondrules is about $p=3\times10^{-2}$.

Considering the probability of a pre-chondrule particle colliding with another particle before solidification, we obtain the ratio of the compound chondrules to all the chondrules (GOODING and KEIL, 1981)

$$p=4\pi a^2 nv\Delta t/\sqrt{2}, \qquad (1)$$

where n is the number density of pre-chondrule particles, v is the mean velocity of pre-chondrule particles just after the heating event of the chondrule formation (we have assumed a Gaussian velocity distribution). This velocity v is considered to have been induced by the mechanical disturbance of the heating event of chondrule formation. We calculate the value of v not by considering the heating mechanisms but by using eq. (1). Thus our results are independent of the mechanism of the heating events.

If the solar nebula was turbulent in the first stage of its evolution, then dust particles stuck to each other to form $\sim10^{-1}$ cm aggregations of dust grains before settling towards the central plane of the solar nebula (WEIDENSCHILLING, 1984). Suppose that a heating event then occurred and the aggregations melted and recondensed to form chondrules. In this case, the number density of pre-chondrule molten particles at the midplane of the solar nebula is calculated using HAYASHI's model (1981):

$$n=6.7\times10^{-11}\left(\frac{\rho_s}{3\ \mathrm{g\ cm^{-3}}}\right)^{-1}\left(\frac{a}{10^{-1}\mathrm{cm}}\right)^{-3}\left(\frac{R}{2\ \mathrm{AU}}\right)^{-11/4}\ [\mathrm{cm^{-3}}], \quad (2)$$

where R is the distance from the Sun and ρ_s is the material density. Substituting eq. (2) into eq. (1), we have

$$v=5\times10^{7}\left(\frac{p}{3\times10^{-2}}\right)\left(\frac{a}{10^{-1}\ \mathrm{cm}}\right)\left(\frac{\Delta t}{10^{3}\ \mathrm{s}}\right)^{-1}\left(\frac{\rho_s}{3\ \mathrm{g\ cm^{-3}}}\right)\left(\frac{R}{2\ \mathrm{AU}}\right)[\mathrm{cm\ s^{-1}}]. \quad (3)$$

It is difficult to explain a velocity as large as $\sim10^8$ cm s^{-1} in the solar nebula. From eq. (1), we have $v\propto n^{-1}$; therefore we suppose that the chondrule formation occurred after the settling of dust particles had progressed and the value of n was much larger than that given by eq. (2).

Next, conditions for gravitational stability are examined. In order for the formation of the compound chondrules to have occurred before the fragmentation of the dust layer, the following relation must have been satisfied (SEKIYA, 1983):

$$\rho_d\leq\frac{7.617M_\odot}{4\pi R^3}, \quad (4)$$

where ρ_d is the spatial mass density of the dust layer just before the heating event and $M_\odot$ is the solar mass. Since the spatial mass density might have been reduced during the chondrule formation event owing to dragging by expanding motion of heated gases, we have

$$\frac{4\pi}{3}a^3\rho_s n\leq\rho_d, \quad (5)$$

where n is the number density of pre-chondrule molten particles. From inequalities (4) and (5), we have

$$n\leq n_{cr}=3.6\times10^{-6}\left(\frac{a}{10^{-1}\ \mathrm{cm}}\right)^{-3}\left(\frac{\rho_s}{3\mathrm{g\ cm^{-3}}}\right)^{-1}\left(\frac{R}{2\ \mathrm{AU}}\right)^{-3}[\mathrm{cm^{-3}}]. \quad (6)$$

Eliminating n in inequality (6) using eq. (1), we have a necessary condition for gravitational stability:

$$v_{rel}\geq1.6\times10^{2}\left(\frac{R}{2\ \mathrm{AU}}\right)^{3}\left(\frac{a}{10^{-1}\ \mathrm{cm}}\right)\left(\frac{\rho_s}{3\ \mathrm{g\ cm^{-3}}}\right)\left(\frac{p}{3\times10^{-2}}\right)\left(\frac{\Delta t}{10^{3}\ \mathrm{s}}\right)^{-1}[\mathrm{cm\ s^{-1}}], \quad (7)$$

where $v_{rel}(=3\pi v/4\sqrt{2})$ is the mean relative velocity of particles after the heating event. The condition for the Weber number is then given by

$$We=\frac{2\rho_s a v_{rel}^2}{\sigma}$$
$$\geq 37\times\left(\frac{\sigma}{400\ \mathrm{dyn\ cm^{-1}}}\right)^{-1}\left(\frac{R}{2\ \mathrm{AU}}\right)^{6}\left(\frac{a}{10^{-1}\ \mathrm{cm}}\right)^{3}\left(\frac{\rho_s}{3\ \mathrm{g\ cm^{-3}}}\right)^{3}\left(\frac{p}{3\times10^{-2}}\right)^{2}\left(\frac{\Delta t}{10^3\ \mathrm{s}}\right)^{-2}, \tag{8}$$

where σ is the surface tension whose representative value is taken to be 400 dyn cm^{-1} for silicate melts (KING, 1951). This value of the Weber number is rather large for collisional sticking to have occurred (ASHGRIZ and POO (1990) conducted extensive experiments involving collisions of water drops and found that drops coagulate in the case where $We\leq10$ for almost all the impact parameters). If sticking is impossible, it is concluded that the compound chondrule formation could not have occurred by collisional sticking in the stage where dust particles were floating in the asteroid region of solar nebula and we must consider (a) other mechanisms of compound chondrule formation (*e.g.* WASSON *et al.*, 1995), (b) chondrule formation occurred during the stage of the planetesimal collisions, or (c) in different regions in the solar nebula (see Section 4). This conclusion is not altered even if we change the solar nebula model, since no model parameters such as temperature and surface density appear in (8). The planetesimal formation may have occurred several times in the same region of the solar nebula (GREENBERG *et al.*, 1984). The above conclusion is not affected by the mechanism of planetesimal formation since only inequalities (4) and (5) were used in our analysis.

4. Discussion

From inequality (8), the minimum value of the Weber number is inversely proportional to square of the cooling time Δt. We used $\Delta t=10^3$ s as a representative value. KITAMURA *et al.* (1987) and WEINBRUCH and MÜLLER (1995) obtained slower cooling rates from exsolution structure in pyroxene, *i.e.*, several to several tens °C/hr. However, these rates are valid only for subsolidus temperatures and are therefore not considered to be directly relevant to the cooling rate in the stage of compound chondrule formation.

There is a possibility that the chondrules were formed in the inner region of the solar nebula. In this case, the lower limit of the Weber number should be reduced according to inequality (8) (*e.g.*, $We\geq0.57$ for $R\approx1$ AU, then molten chondrules would stick to each other since the value of theWeber number could be much smaller than 10). This means that the critical density of the gravitational instability increases as the distance from the Sun decreases, since the tidal force of the Sun increases. The lower limit of the relative velocity then decreases in inverse proportion to the critical density.

Another possibility is that the chondrules were formed after the commencement of the gravitational instability, but before the dust particles settled to form the planetesimals, *i.e.*, the contracting stage of fragmented dust layer. Assuming spherical symmetry of the fragment and neglecting the effects of solar gravity, Coriolis and the centrifugal forces, we have the equation of motion (NAKAGAWA *et al.*, 1986):

$$\frac{\mathrm{d}v_r}{\mathrm{d}t}=-\frac{GM_r}{r^2}-\frac{\rho_g c_t v_r}{\rho_s a} , \tag{9}$$

where v_r is the radial velocity, M_r is the mass inside the sphere with the radius r, and ρ_g is the gas density of the solar nebula. In the case of the minimum mass solar nebula model (HAYASHI, 1981), the gas density on the midplane is given by

$$\rho_g=2.0\times10^{-10}\left(\frac{R}{2\ \mathrm{AU}}\right)^{-11/4} [\mathrm{g\ cm^{-3}}], \tag{10}$$

Further, c_t is the mean thermal velocity of gaseous molecules given by

$$c_t=2.0\times10^{-5}\left(\frac{R}{2\ \mathrm{AU}}\right)^{-5/4} [\mathrm{cm\ s^{-1}}]. \tag{11}$$

Note that EPSTEIN's law (1924) is used in eq. (9), since the mean free path of the gaseous molecules are much larger than the particle radius a. Assuming $\mathrm{d}v_r/\mathrm{d}t=0$, which gives the terminal velocity, and using eqs. (6), (9), (10) and (11), we have the time scale of contraction:

$$\tau=\frac{r}{|v_r|}=3.2\times10^2\left(\frac{a}{0.1\ \mathrm{cm}}\right)^{-1}\left(\frac{\rho_s}{3\ \mathrm{g\ cm^{-3}}}\right)^{-1}\left(\frac{n}{n_{cr}}\right)^{-1}\left(\frac{R}{2\ \mathrm{AU}}\right)^{-3} [\mathrm{years}]. \tag{12}$$

Since , $\tau \propto n^{-1}$, the time interval of the stage where $n \gg n_{cr}$ (*i.e.*, the number density of dust particles is large enough to form compound chondrules with small relative velocities) is very short. Thus, the probability that the chondrule formation event occurred in such a short time interval seems to be small; provided that the energy source of the melting of pre-chondrule particles was related to the contraction of the fragment of the dust layer. The gravitational energy liberated by the contraction was, however, very small; only enough to raise the material temperature about 1 deg at most. Thus, there seems to be no factor for the chondrule formation to occur in the contracting stage of the gravitationally fragmented dust layer. The above discussion is not altered if the contraction of a fragment stopped due to the centrifugal force. In this case, the fragment would have been flattened and subsequent gravitational instabilities should have occurred to make smaller fragments which contracted further.

5. Conclusions

If a compound chondrule was formed by the collision of a plastic pre-chondrule particle with a solid particle or another plastic pre-chondrule particle as considered by GOODING and KEIL (1981), the following conclusions are derived:

(1) Chondrule formation occurred after the settling of dust particles had progressed and the number density of dust particles had increased by several orders of magnitude.

(2) To reproduce the observed ratio of the compound chondrules to all the chondrules, collisional velocities of pre-chondrule particles must have been larger than about

1.6 m s^{-1}, and the Weber number for the collision of molten pre-chondrule particles must have been larger than about 40, if we assume that the chondrule formation occurred in the asteroid region in the stage where dust particles were floating in the solar nebula. In this case, collisional sticking seems to be difficult. If sticking is impossible, then we have to consider other formation mechanisms for the compound chondrules (*e.g.*, WASSON *et al.*, 1995).

(3) There is a possibility that the chondrules were formed in inner regions of the solar nebula. In this case, the lower limits of the relative velocity and the Weber number would be reduced.

In any case, future experimental investigations of molten silicate particle collision are necessary to recognize whether or not the compound chondrules were formed by collisional sticking.

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Appendix

We have investigated 50 thin sections of H3, L3, LL3 and carbonaceous chondrites in the Yamato-74 to -79 and Allan Hills-76 to -78 collections by using an optical microscope. Chondrules and compound chondrules were identified based on the classifications proposed by GOODING and KEIL (1981) and WASSON (1993), respectively. We found 19 compound chondrules in 2490 chondrules in H chondrites, 31 compounds in 2668 chondrules in L chondrites, 8 compounds in 570 chondrules in LL chondrites and 7 compounds in 758 chondrules in C chondrites (Table A1). Some photographs are shown in NAKAMURA *et al.* (1995). Thus, the observed ratios of compound chondrules are 0.76, 1.16, 1.40 and 0.92 % in H, L, LL and C chondrites, respectively. An average ratio of compound chondrules in the four types of chondrites is estimated to be ~1 %. Abbreviations used in Table A1 are Pri./Sec. = types of primary and secondary chondrules in a compound chondrule, Ad, Co and En = adhering, consorting and enclosing types of compound chondrule, respectively, and PO, POP, RP, BO and C = porphyritic olivine, porphyritic olivine-pyroxene, radial pyroxene, barred olivine and cryptocrystalline chondrule, respectively.

Table A1. Compound chondrules in Antarctic chondrites.

H3 chondrites	Chondrules	Compounds	Type	Pri./Sec.
ALH-77299	155	3	Ad	RP/RP
			Ad	BO/RP
			Ad	BO/BO
ALH-78084	337	2	Ad	BO/BO
			Co	RP/RP
Y-74138	31	0		
Y-74142	128	2	Ad	BO/BO
			Co	BO/POP
Y-75028	62	1	Co	PO/PO
Y-790161	454	3	Co	BO/PO
			Co	RP/RP
			Co	RP/RP
Y-791038	342	3	Co	POP/POP
			Co	C/BO
			En	BO/POP
Y-791057	139	1	Ad	RP/RP
Y-791087	212	0		
Y-791428	412	3	Ad	C/RP
			Ad	BO/BO
			Ad	BO/BO
Y-791500	218	1	Co	PO/POP
Subtotal	2490	19		

Table A1. (continued)

L3 chondrites	Chondrules	Compounds	Type	Pri./Sec.
ALH-77011	199	5	Co	RP/RP
			Ad	BO/BO
			Co	POP/PO
			Co	RP/C
			Co	BO/PO
ALH-77015	102	4	Co	RP/RP
			Ad	BO/POP
			Co	RP/RP
			En	BO/POP
ALH-77032	69	1	Ad	BO/PO
ALH-77048 L/LL	71	0		
ALH-77050	196	0		
ALH-77052	196	5	Ad	RP/RP
			Ad	BO/BO
			Ad	POP/POP
			Co	POP/POP
			En	RP/POP
ALH-77075 L/LL	35	0		
ALH-77140	88	0		
ALH-77167	143	1	Ad	RP/RP
ALH-77176	70	1	Ad	RP/PO
ALH-77185	90	0		
ALH-77249	160	2	En	BO/POP
			Ad	PO/PO
ALH-77260	81	0		
ALH-78041	210	1	En	POP/POP
ALH-78046	39	2	En	BO/POP
			Co	C/C
ALH-78162	169	1	En	POP/POP
ALH-78235	65	0		
ALH-78239	52	0		
Y-74024	47	0		
Y-74033	46	1	Ad	PO/POP
Y-74191	214	5	Ad	BO/BO
			En	POP/PO
			Ad	POP/BO
			En	BO/PO
			Ad	BO/POP
Y-74441	111	1	Ad	BO/BO
Y-75273 L/LL	84	1	Ad	BO/BO
Y-791429	131	0		
Subtoal	2668	31		

Table A1. (continued)

LL3 chondrites	Chondrules	Compounds	Type	Pri./Sec.
ALH-764	188	2	Ad	BO/BO
			Co	BO/PO
ALH-77278	99	1	An	C/C
ALH-78015	111	2	En	BO/BO
			Ad	BO/BO
Y-74171	70	1	Co	PO/PO
Y-74660	89	2	En	BO/POP
			Ad	RP/RP
Y-75106	13	0		
Subtoal	570	8		

Table A1. (continued)

C3 chondrites		Chondrules	Compounds	Type	Pri./Sec.
ALH-77003	C3	113	1	Ad	BO/BO
		12	0		
ALH-77307	CM2	136	1	Co	PO/PO
ALH-78261	CM2	16	0		
Y-74135	CO3	149	2	Ad	POP/PO
				En	PO/PO
Y-74642	CM2	56	2	Co	PO/PO
				Co	PO/POP
Y-74662	CM2	143	0		
Y-75260	CV3	13	0		
Y-75293	CM2	120	1	En	PO/POP
Subtotal		758	7		
Total		6486	65		