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Compound chondrule formation via collision of supercooled droplets

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ABSTRACT

We present a novel model showing that compound chondrules are formed by collisions of supercooled droplets. This model reproduces two prominent observed features of compound chondrules: the nonporphyritic texture and the size ratio between two components.

1. Introduction

Chondrules are spherical particles of 0.1–1 mm in size contained within chondrites, the most common type of meteorites, as a major component. The volume fraction of chondrules in typical chondrites, i.e., ordinary chondrites, is up to 70% (Rubin, 2000). It implies that the total mass of all the chondrules in all the asteroids would be very large. This cannot be ignored compared to the total solid mass in the asteroid belt. The ages of chondrules are about 4.6 Gyr, slightly (probably a few Myr or less) younger than the Calcium-Aluminum-rich Inclusions (CAIs) (e.g., Dauphas and Chaussidon, 2011). Therefore, the formation of chondrules must be related to the formation of the solar system itself, especially to the formation of the asteroids, the rocky planets, and probably Jupiter as well. Revealing the chondrule formation process, therefore, is one of the keys to elucidating the Solar System formation. Chondrules are thought to be melted by some heating processes in the early solar nebula and become spherical due to the surface tension. However, heating processes responsible for chondrule formation and their details remain unclear.

Studies of chondrules in thin sections have revealed that some chondrules are composed of two or more chondrules fused together. They are called *compound chondrules*. The presence of compound chondrules is interpreted to be the result of collisions among non-solid precursors. Since the compound chondrule formation includes multiple precursors, it is a more complicated phenomenon than single chondrule formation. It suggests that by studying compound chondrule formation, we can obtain more information on the chondrule formation process itself, since it is likely that compound chondrules and single chondrules are formed by similar mechanisms. Determining the compound chondrule formation process is an important issue to be addressed.

Previous studies on compound chondrule formation mainly analyzed the fraction of compound chondrules among all the chondrules, which is expressed by $f_{\rm compound}^{\rm ALL}$ and is about 4% ($f_{\rm compound}^{\rm ALL} = 4 \times 10^{-2}$) (Gooding and Keil, 1981). Most of the previous studies assume that compound chondrules are formed by collisions of molten precursors (the molten-collision model) (e.g., Ciesla et al., 2004). The fraction of compound chondrules was estimated from the fraction of chondrules undergoing collisions with other chondrules (Gooding and Keil, 1981; Ciesla et al., 2004). The fraction of chondrules that underwent collisions with others, $f_{\rm col}$, can be estimated by

$$f_{\rm col} = n\sigma v t_{\rm col}, \tag{1}$$

where n is the number density of chondrules, σ is the collisional cross section, v is the collision velocity, and $t_{\rm col}$ is the duration of time when compound chondrule forming collisions take place. Each quantity may be evaluated as follows. A typical radius of chondrules r is about 2×10^{-2} cm (Rubin, 2000), and the collisional cross section of chondrules σ is about $\sigma \sim \pi(2r)^2 = 5 \times 10^{-3}$ cm^2. We assume that the collision velocity is $v = 1 \times 10^2$ cm s^{-1} from hydromechanical constraints (e.g., Ashgriz and Poo, 1990). As for the duration of time when chondrules stay molten, it is suggested to be shorter than 10^4 sec based on the cooling rate estimation of chondrule formation (Desch and Connolly, 2002), or some studies suggest that the duration of time when chondrules stay molten is only a few sec

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(e.g., Yurimoto and Wasson, 2002). In order to reproduce the observed fraction of compound chondrules, $f^{ALL}_{compound} = 0.04$, the number density n should be 8×10^{-6} cm^{-3} or much higher. Using a similar argument, Ciesla et al. (2004) inferred that chondrules would have formed in regions of the solar nebula that had highly concentrated solids. However, it is not clear if such a concentrated region can be present in the early solar nebula. For example, when we suppose that compound chondrules are formed in the mid-plane of the minimum mass solar nebula (Hayashi, 1981) at 2 AU, and suppose that the dust-to-gas mass ratio is raised to be unity due to dust sedimentation, and suppose that all the dust forms chondrule precursor particles, then the estimated number density of chondrule precursor particles would only be about 2×10^{-6} cm^{-3} when the internal density of precursor particles is about 3 g cm^{-3}. Since the values of σ and v_c would not be changed significantly, the short duration t_{col} requires a higher number density n to form the large fraction of compound chondrules.

Compound chondrules have some other noteworthy features. A component in a compound chondrule usually holds spherical shape, which is called *primary*. In contrast, the other component is usually deformed and called *secondary*. The median size ratio of primary to secondary is approximately four (Wasson et al., 1995); i.e., the spherical primary is typically four times larger than the deformed secondary. In addition, compound chondrules can be grouped into three types according to structure (Wasson et al., 1995): (1) an adhering type, wherein a small secondary is stuck on a large primary, (2) a consorting type, where both primary and secondary have roughly the same size, and (3) an enveloping type, where a secondary encloses a primary. In ordinary chondrites, it is found that enveloping compound chondrules are rare (only eight out of 80 samples or about 10% of all the compound chondrules) (see Wasson et al., 1995), so in this study we consider only the adhering and the consorting types. According to Wasson et al. (1995), the fraction of the adhering type is $66/80 = 82.5\%$ and that of the consorting type is $6/80 = 7.5\%$.

The textures of chondrules contained in compound chondrules have another noteworthy feature. In general, the textures of chondrules are classified into three types: porphyritic, nonporphyritic, and glassy. According to Gooding and Keil (1981), only 16% of all the chondrules are nonporphyritic chondrules, while 84% of them are porphyritic. Glassy chondrules are extremely rare (Krot and Rubin, 1994). In contrast, when we look at components in compound chondrules in ordinary chondrites, we can find that most of them have nonporphyritic texture. Although the majority of compound chondrules in CV chondrites is porphyritic, the trend ($f^{NP}_{compound}/f^{ALL}_{compound} \gg 1$) is common (Akaki and Nakamura, 2005), where $f^{NP}_{compound}$ is the fraction of compound chondrules in nonporphyritic chondrules. Wasson et al. (1995) revealed that 52 primaries and 65 secondaries in 72 adhering and consorting compound chondrules are nonporphyritic, so the fractions of the nonporphyritic type are $52/72 = 81\%$ for the primary and $65/72 = 90\%$ for the secondary, both of which are much higher than the fractions in all the chondrules. Experimental studies showed that nonporphyritic chondrules are formed from completely molten droplets, and porphyritic ones are formed from partially molten particles (e.g., Connolly et al., 1998). Therefore, it is strongly suggested that compound chondrules are formed mainly from completely molten droplets, while single chondrules are formed from partially molten particles.

Experiments (e.g., Nagashima et al., 2006; 2008) showed that completely molten levitated droplets having no contact with any other solids turned into a supercooled state at their liquidus temperature as they are cooled. The supercooled droplets behaved as fluid particles even at a temperature lower than the liquidus.

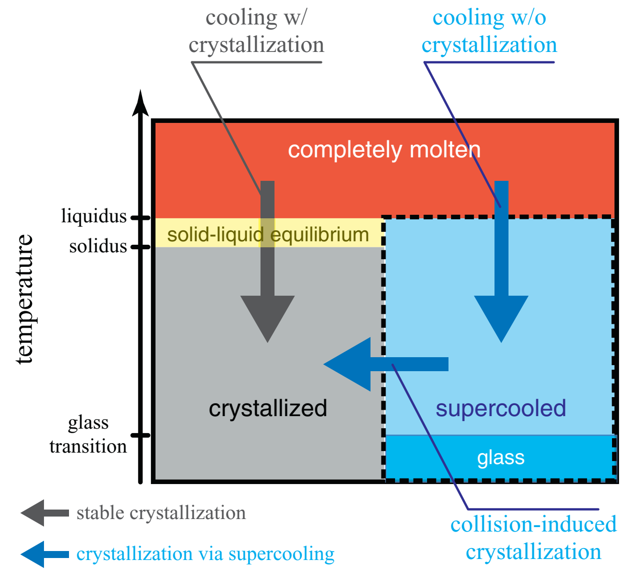

Fig. 1. A schematic phase diagram of dust particles in stable states (completely molten, solid-liquid equilibrium, and crystallized) and metastable states (supercooled and glass). Previous studies considered that nonporphyritic chondrules are crystallized between their liquidus and solidus (gray arrow). In contrast, completely molten levitated droplets invariably turn into supercooled droplets and these supercooled droplets turn into crystallized particles by contact (blue arrows). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

If the temperature is maintained properly, the droplets remained supercooled for a long time. However, when the droplets collide with a solid particle, they immediately crystallize and form a nonporphyritic texture. Since the majority of components in compound chondrules are likely to be formed from completely molten droplets, it seems natural to expect that most of the compound chondrules have experienced a supercooled state in their formation process. However, the supercooling has never been taken into consideration in the context of compound chondrule formation.

In this study, compound chondrule formation with supercooling is examined. Table 1 lists some apparent features and the number of observed compound chondrules, which should be explained by a successful compound chondrule formation model. We will address these properties, and we will see that they can be explained by taking the supercooling into account in the model.

2. Crystallization of melts

Understanding the crystallization mechanism is essential for discussing the formation process of compound chondrules. However, in previous studies of compound chondrule formation, the crystallization process was considered incorrectly. For example, Hubbard (2015) assumed that the viscosity of dust particles changed continuously from the liquidus temperature to the glass transition point; however, in reality, the viscosity increases discontinuously at the solidus temperature.

Fig. 1 shows a schematic phase diagram of dust in stable states (completely molten, solid-liquid equilibrium, and crystallized) and metastable states (supercooled and glass). A metastable state is an unstable equilibrium state of a macroscopic system in which the system can remain for a long period. A supercooled droplet and a glass particle are well-known examples of metastable states.

In stable states, as the temperature decreases, completely molten droplets (colored by red in Fig. 1) turn into partially molten particles (solid-liquid equilibrium phase, yellow) at their liquidus (∼1700–2000 K) (Hewins and Radomsky, 1990), and