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An experimental study of chondrule formation from chondritic precursors via evaporation and condensation in Knudsen cell: Shock heating model of dust aggregates

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ABSTRACT

Chondrules, igneous objects of ∼1 mm in diameter, formed in the earliest solar system via a transient heating event, are divided into two types: main (type I, FeO-poor) and minor (type II, FeO-rich). Using various chondritic materials for different redox conditions and grain sizes, chondrule reproduction experiments were carried out at IW-2 to IW-3.8, with cooling rates mainly ∼100 °C/h, with peak temperatures mainly at 1450 °C, and mainly at 100 Pa in a Knudsen cell providing near chemical equilibrium between the charge and the surrounding gas at the peak temperatures. Vapor pressures in the capsule were controlled using solid buffers. After and during the significant evaporation of the iron component from the metallic iron-poor starting materials in near equilibrium, crystallization occurred. This resulted in the formation of a product similar to the type I chondrules. Dusty olivine grains occurred in charges that had precursor type II chondrules containing coarse ferroan olivine, but such grains are not common in type I chondrules. Therefore fine-grained ferroan matrices rather than type II chondrules are main precursor for type I chondrules. The type I chondrules would have evolved via evaporation and condensation in the similar conditions to the present experimental system. Residual gas, which escaped in experiments, could have condensed to form matrices, leading to complementary compositions. Clusters of matrices and primordial chondrules could have been recycled to form main-generation chondrules originated from the shock heating.

1. Introduction

Chondrules, small spherical shaped igneous objects, approximately 1 mm in diameter, are the main constituents of chondrites. They formed via transient heating events in dust-enriched systems in the earliest solar system, possibly in the solar nebula (e.g. Ebel and Grossman, 2000). A lot of models have been proposed for the formation mechanism of chondrules: nebula bipolar flow (Shu et al., 1996), nebula shock wave heating (e.g. Morris and Desch, 2010), shock wave heating by planetesimal collisions (Libourel and Krot, 2007), shock wave heating on the debris cloud produced by impacts between planetesimals (Ruzicka, 2012), X-ray flares from the early sun (Connolly et al., 2006), and asteroidal origins (Hutchison, 1996). More recently, Fedkin and Grossman (2013) proposed chondrule formation through impact-generated plumes based on the lack of a large depletion of alkalis elements in natural chondrules (e.g. Alexander et al., 2008) and the small isotopic fractionations of rock-forming elements (Si and Fe) (e.g. Mullane et al., 2005; Hezel et al., 2010; Dauphas et al., 2015).

Chondrules are compositionally divided into two types: type I and type II. Type I chondrules are characterized as being FeO-poor (Fe# = 0–10), whereas type II chondrules are characterized as being FeO-rich (Fe# > 10) (where Fe# is defined as $100 \times x_{Fe}/(x_{Mg} + x_{Fe})$, and x_{Mg} and x_{Fe} indicate the molar fraction in olivine and low-Ca pyroxene) (e.g. McSween et al., 1983). Type I chondrules are subdivided into IA (olivine dominant), IAB (olivine and pyroxene dominant), and IB (pyroxene dominant) (Scott and Taylor, 1983). Type I chondrules are alkalis-depleted and type II chondrules are alkalis undepleted (Hewins, 1991; Hezel and Palme, 2010; Fedkin and Grossman, 2013). The evidence of alkalis and sulfur in chondrules would suggest the volatile saturated (Alexander et al., 2008) or volatile recondensation condition (e.g.

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Hewins, 1997) during the chondrule formation. Type II chondrules have been successfully reproduced experimentally under pressures of 1 bar and an oxygen fugacity of 0.5 order magnitude below the iron–wüstite buffer (IW-0.5) (e.g. Tsuchiyama et al., 1980).

The reproduction of type I chondrules, which consist of forsterite and enstatite, has been attempted less, probably because they may formed at high temperatures and under more reduced conditions. Cohen and Hewins (2004) carried out chondrule formation experiments under reduced conditions of IW-3 to −5; however, they were isothermal experiments. Lofgren and Le (2002) used carbon in an evacuated silica tube to successfully reproduce type I chondrule textures. The present study focuses on the reproduction of type I chondrules using various kinds of chondritic precursors under the oxygen fugacity parameters of IW-2 to −3.8 in an open system.

Tenner et al. (2015) argued that type I chondrules formed in a ×100 dust-enriched system (IW-3) and type II in a ×2500 dust-enriched system (IW), and suggested that two sources of oxygen isotopes exist, low $\Delta^{17}O$ and ^{16}O-rich source for type I chondrules and high $\Delta^{17}O$ and ^{16}O-poor source for type II chondrules.

The interaction of chondrule melt with H_2O and SiO gases has been strongly suggested based on oxygen isotopic analyses from experimental studies (Yu et al., 1995) and primitive chondrules (e.g. Chaussidon et al., 2008). Chaussidon et al. (2008) and Yurimoto and Kuramoto (2004) found evidence in the chondrules to suggest that a ^{16}O-rich precursor reacted with ^{17}O- and ^{18}O-rich gases. Based on this evidence, they modeled the evolution of chondrules in the solar nebula. Tissandier et al. (2002) experimentally examined the interaction of the SiO-rich gases of the chondrule melts. The results indicated that rapid formation of low-Ca pyroxenes occurred through condensation of Si-rich gas in the silicate melt in the CaO–MgO–Al_2O_3–SiO_2 system (without H_2 and Fe).

Various chondrule precursors have been suggested, including ferroan silicates, forsterites (Jones, 1996), polymict dust balls (e.g. Hewins and Zanda, 2012), ferroan precursors based on the precipitation of reduced iron metal in relict olivine (e.g. Nagahara, 1981), lithic fragments of planetesimals (Libourel and Krot, 2007), the amoeboid olivine aggregates (AOAs) and calcium aluminum rich inclusions (CAIs) (Krot et al., 2004), clasts from comets (Kitamura and Tsuchiyama, 1996), and type I chondrule for type II chondrule (Villeneuve et al., 2015).

To reproduce type I chondrules, the present experimental system was designed, satisfying plausible chondrule formation conditions, where the evaporation from the Knudsen cell suppresses the isotopic fractionation, showing non-Rayleigh fractionation (Young et al., 1998; Mullane et al., 2005; Hezel et al., 2010; Dauphas et al., 2015). The Knudsen cell prevented the isotopic fractionation of rock forming elements (Si and Fe) with an oxygen fugacity controlled using solid buffers (silica and metallic iron) as explained in Appendix A. The present experimental results suggest that fine-grained ferroan matrices are a precursor component of the type I chondrules. A new chondrule formation model with recycling and evaporation of chondritic aggregates, consisting of type I chondrules and matrices is proposed, considering that chondrules and matrices are complementary (Hezel and Palme, 2010).

2. Experiments

2.1. Furnace assembly

Fig. 1a shows a schematic view of the newly installed vacuum furnace (Nikkato). The total pressure in the furnace is arbitrarily controlled by a butterfly valve (Fuji Technology) to less than ∼10000 Pa. The pressure was measured by a diaphragm-seal type pressure gauge (626 Baratron, MKS Instruments, Andover, MA, USA) (Fig. 1a). The hydrogen gas was introduced through the electric decomposition of water (H2PEM-510, Park Hannifin Corp.) through a flow meter (Gasblender GB-2C, Kofloc) (Fig. 1a). The oxygen gas from decomposed water was exhausted into air.

The total pressure was controlled to remain mainly at 100 Pa, and only a few runs were undertaken at pressures of 1 Pa (AfS-7), 2 Pa (AfS-11), 10 Pa (AfS-8), and 1200 Pa (A4S-3, A4I-2, and S5I-1). The flow rate was approximately 50 cc/min. The peak temperature of the furnace was controlled to be less than 1550 °C. The temperature of the furnace was controlled by the W–Re thermocouple (TC1), and the temperature in the capsule was nearly identical to that of TC1 (Fig. 1a).

2.2. Capsules

Three types of Knudsen cell, made of alumina capsules (SSA-S, Nikkato), each with a small orifice of 0.9 mm in diameter were used for the present study. Thus the charge in the interior of the capsule is nearly in equilibrium with the surrounding gas (e.g. Sata et al., 1978). Molybdenum wire of 0.2 mm in diameter was mainly used for charge holding but platinum or iridium wire and carbon-rod were also used (Table 1). Three experimental setups were used: capsule 1 with no solid buffer (Fig. 1b) capsule 2 with SiO_2 powder on the bottom (Fig. 1c), and capsule 3 with iron powder on the bottom (Fig. 1d) with different charge-gas interaction as explained in Appendix A.

Hydrogen gas was introduced into the capsules during heating (Fig. 1a). The interior vapor pressure in the capsule (approximately 1 Pa) was lower than the hydrogen gas pressure (approximately 100 Pa); therefore, the total pressure in the capsule nearly equaled the molecular hydrogen pressure. The present experimental design thus enables the nebula conditions with hydrogen gas dominant. At the peak temperature of 1450 °C, the oxygen fugacity was IW-2 to −3.8. At similar temperatures when the total pressure was 1–10 Pa and 1200 Pa, the oxygen fugacity was calculated to be IW-2 and IW-4.5, respectively. The oxygen fugacity (mainly IW-2 to −3.8) therefore includes that of type I chondrules (IW-2 to −4, Zanda et al., 1994; IW-2, Grossman et al., 2012; IW-3.5, Villeneuve et al., 2015). The detailed thermochemical calculations for the interior conditions in capsules 1–3 are shown in Discussion and Appendix A (Supplementary Material).

2.3. Starting materials

Seven types of starting materials with natural and synthetic chondritic compositions were prepared, including the Allende fragments (Af) and the sintered pellets of the powders (A3, A4, NW, S2, S3, and S5), where A stands for Allende, NW for the ungrouped chondrite NWA 1465, and S for synthetic (Fig. 2; Table B1 in Appendix B). The procedure for making sintered pellets is shown: the powders were pressed to make pellets using a stainless tool with a 3-mm diameter and 2-mm thickness, and the pellets were sintered during heating and cooling at rates of 270 °C/h, where a maximum temperature of 950 °C was sustained for one minute under the oxygen buffers of IW for A3, and less than IW for A4, NW, S2, S3, and S5. The initial weight of the sintered pellets was approximately 11–34 mg (Table 1). The grain size of the starting materials is in the range of sub mm–sub µm, and is suitable for the possible precursors.

The starting materials were broadly divided into two types: metallic iron-poor (but FeO rich) (Af, A3, A4, and NW) and metallic iron-rich (but FeO poor) (S2, S3, and S5). The main difference between metallic iron-poor types of the Allende and NWA 1465 chondrites is that the coarse grained olivines and low-Ca pyroxenes constituting chondrules in Allende are mainly type I and therefore magnesian but accompanying many thermally metamorphic