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A synthesis experiment of GEMS analogue grains produced by thermal plasma

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Anhydrous IDPs (interplanetary dust particles), which is considered to have cometary origin, have a large amount of amorphous matter called GEMS (glass with embedded metal and sulfides). This is typically a few 100 nm in diameter and consists of SiO_2-rich silicate glass including small (typically 10-50 nm) and rounded grains of Fe, Ni metals and sulfides. There are two formation models proposed for GEMS: (1) condensate of Si-rich gas [1], and (2) amorphization of crystalline silicate dust [2]. It is important to reproduce GEMS analogue matter in a laboratory to understand conditions for GEMS formation process. Especially, we focused on whether or not amorphous silicate spheres that contain nano-grains of metal can be formed by condensation from a Si-rich gas in this study.

The Si-rich gas was obtained by using an induction thermal plasma (ITP) (TP12010, JEOL). The ITP can provide ultra-high temperature (~10,000 K) to evaporate a starting material immediately, and then, the gas is quenched rapidly with the cooling time scale of 10^4-10^5 K/sec to form nanoparticles, which are usually in an amorphous state. Powders of MgO, metallic Fe and SiO_2 were mixed together with the GEMS mean composition [1] (Mg/Si = 0.65, Fe/Si = 0.56) for preparing the starting material, which was an analogue to Si-rich gas in the early solar system. Mg, Si, Fe and O were taken into consideration as major elements in solid materials in the solar system for simplicity. It was proposed that GEMS was condensate as amorphous silicate including metals, and then, the metals near the surface of GEMS were sulfurized [1]. Moreover the experimental difficulty, we carried out this study with S-free system. The ITP experiments were produced under an Ar-He atmosphere at atmospheric pressure.

Run product attached on the chamber walls of the furnace was collected. Iron and amorphous silicate are identified by powder X-ray diffraction (XRD) pattern. No crystalline silicates, such as forsterite, pyroxene and silica mineral, are detected. Thus, amorphous silicate was formed directly from high-temperature gas by very rapid condensation. Micrographs by transmission electron microscope (TEM) show that the run product is composed of numerous spherical grains (typically ~50 nm in diameter) and each grain has an iron core (~20 nm in diameter) embedded in an amorphous silicate.

Yamamoto & Hasegawa (1977) theoretically formulated homogeneous nucleation and growth of dust grains from a gas, proposed a non-dimensional parameter for the condensation and calculated the value for some astronomical environments such as presolar nebula at 0.1 AU (~$3x10^9$) or around AGB stars (0.9-90) [3]. This value in the present experiments was estimated to be ~$4x10^3$. This was not the same as but not extremely different from those in the astronomical events.

The textures of the run product are similar to that of GEMS, although, GEMS is composed of multiple metal grains. It means that sintering a number of amorphous silicate spheres including a metal grain can form the GEMS-like texture. Solar system origin of GEMS is proposed based on that GEMS has rare oxygen isotopic anomalies [1]. However, if GEMS was a mixture of primary grains of a few tens nm in size, exchanging of oxygen atoms between the primary grains and surrounding gas, which contained large amounts of H_2O and CO molecules, might occur even at low temperatures, and the oxygen isotopic anomalies disappeared in most GEMS. Therefore, the rare oxygen isotopic anomalies of GEMS might not be evidence of the solar system origin. Primary grains of GEMS might originally form around evolved stars by condensation, were transferred to interstellar region, incorporated into the primordial solar nebula, suffered by oxygen isotope exchange with surrounding gas, and accumulated into GEMS. Finally some iron grains near the GEMS surfaces were sulfurized.

[1] Keller & Messenger, 2011 [2] Bradley & Dai, 2004 [3] Yamamoto & Hasegawa, 1977

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