Crystallization of amorphous Mg-Fe silicate with olivine stoichiometry in protoplanetary disks

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In the past couple of decades, astronomical observations have found that almost all interstellar silicate particles are amorphous and crystallize in the hot part of circumstellar disks ([1] Molster et al., 1999; [2] Kemper et al., 2004; [3] Ábrahám et al. 2009). Pristine chondritic meteorites (e.g. DOM 08006) include such amorphous silicate whose compositions are equivalent to olivine or pyroxene with wide range of Fe-content (e.g. [4] Davidson et al. 2019). Although crystallization kinetics of amorphous silicate dust is essential for constraining the thermal condition of disks to preserve amorphous silicate from crystallization, kinetics of crystallization of Fe-bearing silicate at low pressure has not been fully understood. Here we synthesized Fe-Mg amorphous silicate nano-particles with a stoichiometry of olivine ($(Mg, Fe)_2SiO_4$) using a radio-frequency inductive thermal plasma method at Nisshin Engineering Co. Ltd. We annealed them in vacuum at 580–750°C for 1–162 h, and analyzed their morphology, chemical compositions, and crystallinity with FE-SEM-EDS, FT-IR, and XRD.

The synthesized dust analogue used as a starting material of annealing experiments mainly consisted of olivine-like amorphous nanoparticles (Fo#:=Mg/(Mg+Fe)~70%), but also included lumps of amorphous silicate powder with a pyroxene ($(Mg, Fe)SiO_3$)-like stoichiometry and only ~1 vol.% of crystalline olivine (Fo#=59%). The shape of mid-infrared absorbance spectra of annealed samples changed with heating duration. Infrared features of crystalline olivine in the annealed sample were more prominent than amorphous forsterite heated at the same temperature for the same duration ([5] Yamamoto and Tachibana, 2018), suggesting that crystallization of amorphous Fe-Mg silicate proceeds at a faster rate than amorphous silicate. Crystallization degrees of samples heated for various durations are obtained based on the absorption features in the wavelength range of 8–13 μm. The timescales of crystallization of amorphous olivine at 580, 610, 630°C are estimated to be ~1, ~5, and ~19 h, respectively, by applying the Johnson-Mehl-Avrami equation to the time evolution of crystallization degrees. The activation energy for crystallization of amorphous olivine (Fo#=70%) is estimated to be 4.28×10^4 K, which is slightly smaller than that of amorphous forsterite ([5]). More effective crystallization of Fe-bearing amorphous silicate nanoparticles indicates that the disk temperature to prevent crystallization of amorphous dust would be lower than that for amorphous Mg silicates ([5]).

Keywords: protoplanetary disk, crystallization, silicate dust