Systematic Laboratory Study on Chemical Composition of Circumstellar Amorphous Silicate Dust

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Amorphous silicate is a major component of circumstellar and interstellar dust [1, 2]. Infrared spectra of oxygen-rich asymptotic giant branch (AGB) stars, the most prevalent circumstellar dust suppliers in the galaxy, show features at ~10 μm and ~18 μm deriving from amorphous silicate dust. Their peak positions and strength ratios vary among stars, which are explained by (1) optical constants depending on the chemical compositions and structures, and (2) physical parameters such as particle size, temperature, and shape. Artificial materials called "astronomical silicate" [3, 4], have been widely used to interpret observed dust spectra. However, astronomical silicate cannot be used to discuss chemical compositions of observed dust and dust formation processes. Various dust analogues have been produced in laboratories [e.g., 5, 6, 7] yet cannot explain observations better than astronomical silicate. This is partly because the relation between optical constants and chemical compositions of amorphous silicate is not fully understood. Previous experiments are mainly conducted in the system of Mg-Fe-Si-O and experiments regarded in elements, that can change the structure of SiO_4 network (such as Al, Ca, and Na), are limited [8]. Also, the effects of physical parameters such as particle size are poorly considered.

We conducted condensation experiments using an induction thermal plasma (ITP) system (JEOL TP-40020NPS [8]). The chemical compositions of the starting materials were systematically changed from the CI chondritic composition in the systems of Al-Mg-Si with Al/Si ratios of 0.08–0.64 and Al-Ca-Mg-Si with Ca/Mg ratios of 0–1. The condensed particles were analyzed by XRD (Rigaku RINT-2100), EPMA (JEOL JXA-8530F), and TEM (JEOL JEM-2800). IR absorption spectra of the products dispersed in KBr pellets and the reflectance spectra of pressed sample pellets were measured with FT-IR (JASCO FT/IR-4200, Thermo Scientific Nicolet 6700).

The products were mainly spherical amorphous nanoparticles (10–100 nm) and showed little change in the bulk chemical compositions from the starting materials. Optical constants for five samples were determined from absorption and reflectance spectra using the Lorentz oscillators model with/without the KBr medium effect. No set of optical constants replicated both absorption and reflectance spectra, probably because the pressed grains were agglomerated and deformed. Dielectric constants at high frequency determined from the reflectance spectra at ~7000 cm^{-1} (1.4 μm) were used to fit the absorption spectra to obtain optical constants between 390–2500 cm^{-1} (4–26 μm) Absorption spectra of the amorphous silicates without KBr medium effect were calculated with the optical constants determined in this study assuming the spherical-shaped grain of 0.1–10 μm in diameter. We compared the calculated spectra with observed dust emissions of Z Cyg [9]. The 10 μm peak position of Z Cyg was longer than any of the products and the 18 μm peak was located between those of the products with Ca/Mg ratios of 0 and 1. The higher Al and Ca contents than the CI chondritic composition can explain the dust spectra of Z Cyg. These results suggest that circumstellar dust cannot be explained by pure Mg-Fe-silicate dust but by silicate dust enriched in Al and Ca.

[1] Kemper et al., 2004, *ApJ* 609(2), 826. [2] Kemper et al. 2005, *ApJ* 633, 534. [3] Draine & Lee, 1984, *ApJ* 285, 89. [4] Ossenkopf et al., 1992, *A&A* 261, 567. [5] Dorschner, et al., 1995, *A&A* 300, 503. [6] Rietmeijer et al., 1986, *Icarus* 66(2), 211. [7] Speck et al., 2015, *ApJ* 809, 65 [8] Mutschke et al., 1998, *A&A* 333, 188. [8] Kim, A. et al., 2021, A&A 656, A42. [9] Onaka et al., 2002, *A&A* 388(2), 573-586.