Inefficient growth of silicate grains and widespread formation of fractal dust

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Gail and Sedlmayr (2013) predicted that silicate grain growth from SiO vapors would be inefficient based on the principle of detailed balance and studies that demonstrated inhibited evaporation of minerals in vacuum (e.g., Nagahara et al., 1994). Kimura *et al.* (2022) measured the vapor-phase growth efficiency of SiO onto $(SiO_x)_n$ clusters in microgravity and found an efficiency between 0.005 to 0.016. Paquette *et al.* (2023) used an SiO growth coefficient of 0.01 in a model of a circumstellar outflow around an AGB star and found that silicate grain coagulation was significant and resulted in the formation of fractal dust aggregates. Compared to a model with efficient growth, grain sizes were approximately 100 times smaller, grain densities were a million higher, and the coagulation rate increased by a factor of a trillion. While the results are somewhat model dependent and are sensitive to the exact SiO growth efficiency used, low growth efficiency always led to higher number density populations of smaller primary condensates that nearly always led to fractal dust aggregates. The traits of the aggregate populations were sensitive to the number density and size of the primary condensates.

The condensation of SiO_x solid/liquid clusters from SiO vapor is a phase change that requires a considerable chemical driving force (supersaturation) to overcome the unstable intermediate SiO dimers, trimers, and larger clusters before reaching a state (the critical cluster) where the addition of the next SiO monomer produces a more stable species that can continue to grow. The concentration of critical clusters depends on the temperature, the chemical characteristics of the condensing species and the concentration of gaseous SiO. As vapor expands and cools the concentration of critical clusters increases exponentially while the monomer population decreases due to both the formation of new critical clusters as well as to cluster growth. If growth is inefficient, then SiO supersaturation remains higher for longer, more SiO is incorporated into cluster creation and less goes into growth. Since the initial quantity of gas-phase SiO is constant, the higher the concentration of critical clusters, the smaller the final size of each of these primary grains. Since the rate of coagulation depends on the square of the grain density, decreasing the SiO growth efficiency results in a significant increase in the number density of grain aggregates.

We will discuss the implications of the formation of fractal aggregates under conditions where condensation is a rapid, dynamic process and note that the result is very different from that obtained under near-constant conditions where thermodynamic equilibrium controls the speciation and morphology of the solids that are formed. We will also discuss the expected evolution of the fractal grains as they leave the circumstellar envelope.