Grain Formation in Oxygen-Rich AGB Stars

Joseph A. Nuth[1], Frank T. Ferguson[1, 2], Natasha M. Johnson[1], John A. Paquette[1, 2]

[1]NASA's Goddard Space Flight Center, USA, [2]Catholic University, USA,

In theory, the stability of specific minerals can be calculated with reasonable precision in expanding stellar atmospheres provided that the thermodynamic parameters of these solid phases and the chemical composition of the gas are known. Infrared spectroscopic observations of dusty stellar atmospheres can be used to identify the major condensed phases that must be considered in such calculations. Based on this methodology we can predict, to first order, the composition of the dust injected into the interstellar medium from any given star. These results can be misleading.

Unfortunately, grain formation does not occur under equilibrium conditions. Solids form from gas by a kinetically controlled phase transition. Chemical compositions of intermediate phases between the initial gas and the first stable solids are unknown and likely to be highly unstable to both growth and decomposition. In a gas of cosmic composition, the number and complexity of these intermediates is huge and beyond our current ability to model since we not only need the stability of each intermediate but also its reaction rate with each other gas phase constituent.

We have tried to get around these difficulties by conducting a series of experiments. We first measured the conditions under which SiO condensed, then measured the condensation of Mg-SiO and found that the presence of magnesium did not seem to be important for condensation above about 900K. Stephens and Bauer found similar results for the condensation of Fe-SiO. We postulate that nucleation of SiO clusters controls dust condensation in oxygen-rich stars. Analyses of the solids condensed from Fe-Mg-SiO vapors in hydrogen demonstrated that the original grains were either $MgSiO_x$ or $FeSiO_x$ with no $MgFeSiO_x$ condensates, prompting Rietmeijer to suggest that vapor phase growth occurs at metastable eutectic compositions. Mixed $MgFeSiO_x$ only forms via coagulation of fresh condensates followed by Ostwald ripening at high temperatures.

Measuring the rate of spectral evolution of $MgSiO_x$ and $FeSiO_x$ condensates as a function of time and temperature demonstrated that the highly chaotic initial condensates rapidly annealed into more ordered, glassy structures but that the $MgSiO_x$ grains annealed at much lower temperatures than the $FeSiO_x$ condensates. Condensation at metastable eutectics and the much faster annealing of $MgSiO_x$ solids can explain the observation of crystalline forsterite and enstatite dust in some high mass loss rate AGB stars while dust seen in lower mass loss rate stars remains amorphous.

Microgravity experiments have shown that growth of solids from the gas phase is inefficient. For crystalline materials, only a few atoms out of every $\sim 10^5$ that hit a surface are incorporated into the growing particle. For more amorphous grains such as SiO_x, the rate may be as high as a few SiO molecules for every 10^3 that hit the surface. In a circumstellar outflow, nearly all of the SiO in the gas becomes incorporated into the dust via one of two processes: formation of stable SiO_x clusters or the growth of these clusters into larger grains. If grain growth were efficient, then once stable SiO_x clusters formed, these would consume the remaining SiO from the gas and form large dust grains. Since growth is inefficient a larger number of stable nuclei form, resulting in a much higher density of very small dust grains. Because the coagulation rate is proportional to the square of the number density, inefficient growth increases the formation rate of dust aggregates in circumstellar outflows and most likely results in the injection of fractal dust into the interstellar medium. This has interesting consequences for subsequent grain processing in the ISM and in protostellar nebulae.