CONDENSATION OF FORSTERITE AND METALLIC IRON AROUND EVOLVED AND YOUNG STARS.
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Introduction: Recent observation by infrared spectroscopy has revealed the presence of amorphous and/or crystalline silicate dusts around evolved stars or young star discs [e.g., 1-4]. The species, size, shape, composition, and orientation if they are crystalline, of the dusts control the optical properties of dusts, which further control the radiation field of discs. Thus, the formation and growth of dusts are fundamental processes for the evolution of circumstellar and young star discs.

Condensation is a kinetic process that comprises nucleation and grain growth. In both atomistic processes, "sticking coefficient" plays a key role in the nucleation and growth rates, which linearly affects the rate. The coefficient is a number of atoms incorporated into the condensed phase relative to number of colliding atoms to surface of the condensed phase, which ranges from 0 to 1. Therefore, experimental determination of condensation coefficient is crucial for consideration on the evolution time scale of disks.

Condensation coefficients: The condensation rate, J, is shown by the Hertz-Knudsen equation in the kinetic theory of gas molecules in general form of balance between forward and backward reactions,

$$J = (\alpha_{cond}P - \alpha_{evap}P_{eq})/(2\pi mkT)^{1/2},$$

where α_{cond} is the condensation coefficient, P is the pressure, α_{evap} is the evaporation coefficient, P_{eq} is the equilibrium vapor pressure of the species concerned, m is the weight of gas molecule, k is the Boltzman constant, and T is the temperature. The rate also represents the evaporation coefficient when $P_{eq} > P$. Except for vacuum (P=0), experiments give the net condensation or evaporation coefficients and the two coefficients are not obtained independently. Because of experimental difficulties, we have very limited data and only vacuum evaporation coefficients for forsterite, silicate melts with a few different compositions, and metallic iron have been obtained so far.

In the model calculation, [5] assumed α of unity for all the species at all the conditions, whereas, [6-9] used constants of 0.1 for forsterite and enstatite and 1 for metallic iron by assuming that condensation coefficients are the same as evaporation coefficients.

Experiments: We have previously investigated the evaporation coefficient of metallic iron at various ambient pressures from vacuum to equilibrium, and showed that the evaporation coefficient has dependence on the ambient pressure and temperature [10]. The results clearly show that the evaporation coefficient obtained at vacuum should not be extrapolated to any ambient pressures and in particular to condensation conditions. [11] carried out condensation experiments by heating metallic iron and obtaining condensates on an Fe-substrate at lower temperature area in a vacuum chamber. The condensation coefficient was calculated from the condensed flux, which is the weight increase divided by the surface area and time, against incoming flux, which is the weight loss of the source material also divided by the surface area and time, has temperature dependence, although the value is fairly close to unity.

We have newly carried out experiments at various pressures to get condensation coefficients at various degree of supersaturation. The degree of supersaturation was controlled by changing the incoming flux using tubes with various radius with the same length. The condensation coefficient shows weak dependence on the supersaturation degree at a fixed temperature but is very close to unity.

Model: Growth of metallic iron and forsterite in circumstellar environment around evolved stars and in discs of young stars such as solar nebula is evaluated by using the model for grain formation by [5]. The growth rate of grains is shown by the volume of condensing species multiplied by mean velocity of the condensing atoms and concentration of the species in the gas phase. The equation to describe the nucleation rate contains parameter for surface energy, which is normalized by thermal energy, and that for cooling, which is defined as the saturation time scale normalized by the collision time scale, in addition to the condensation coefficient, and it is very sensitive to temperature. The average final size, size distribution, nucleation time, nucleation rate, and number density if metal grains are studied. Physical parameters are surface tension of silicates (8.75×10^{-9} J m^2), that of metallic iron ($1.8 \times 75 \times 10^{-8}$ J m^2), average solar abundance of elements, and cooling time scale (time to lower to 1/e of the temperature) of the solar nebula is 2×10^7 sec.

Crystalline dust formation in astrophysical environments: Figure 1 shows the average grain size of metallic iron and forsterite with α=1 and lower. Alpha for metallic iron, which was experimentally determined, and larger dependence on temperature and pressure is used for forsterite on the basis of smaller evaporation coefficient of forsterite than metallic iron. Λ for the solar nebula at 2A.U. is about 10^6 and that for out flow around evolved stars is less than 100. The average grain size of metal is controlled only by the cooling time scale of gas but not by the condensation coefficient. It is, however, not the case for forsterite, of which grain size is dependent on α; the size becomes smaller with decreasing α, that is, increasing kinetic barrier for condensation.

The average grain size of metallic iron and forsterite in the out flow of evolved stars is very small. In order for them to become large enough to be observed with IR, they should be coalesced to grow in the circumstellar discs by shock heating [12].

Figure 2 shows the size distribution of the grains for the solar nebula conditions. It is clear that the condensation coefficient plays scarce role for metallic iron, which results in similar size distribution irrespective of α. The metal grain is as large as several μm. On the other hand, forsterite grain size is largely dependent on α, and the size distribution is wide when α is 1, but is narrow when $\alpha<1$. The size distribution of forsterite for $\alpha<1$ is a few μm for most grains, which is consistent with astrophysical observation. Although the average grain size and the size distribution of forsterite, however, can vary if the dependence of α on temperature and pressure are different, it would not become larger than metallic iron because α would never be as large as unity for forsterite. In conclusion, silicate dust condensed in the solar nebula should be smaller than metallic iron by about an order of magnitude, and the size distribution is much narrower for forsterite than metallic iron.

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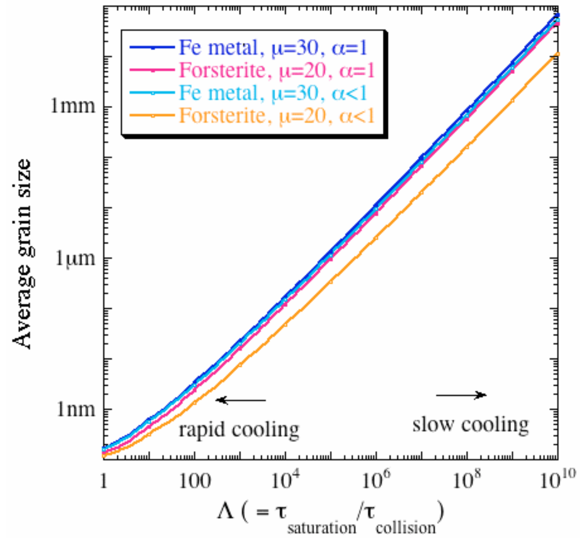

Fig. 1 Average grain size of Fe metal and forsteirte as a function of dimensionless time scale, Λ, which represents the relative time scale of saturation of gas to collision ($= \tau_{saturation}/\tau_{collision}$) and which further represents the relative cooling rate of gas. μ is the dimensionless surface energy normalized by thermal energy (30 for metallic iron and 20 for silicates at the condensation temperature), α is the condensation coefficient, which is a function of temperature and saturation degree obtained in the experiments. $\alpha=1$ represents no kinetic barrier and $\alpha<1$ with kinetic barrier for condensation.

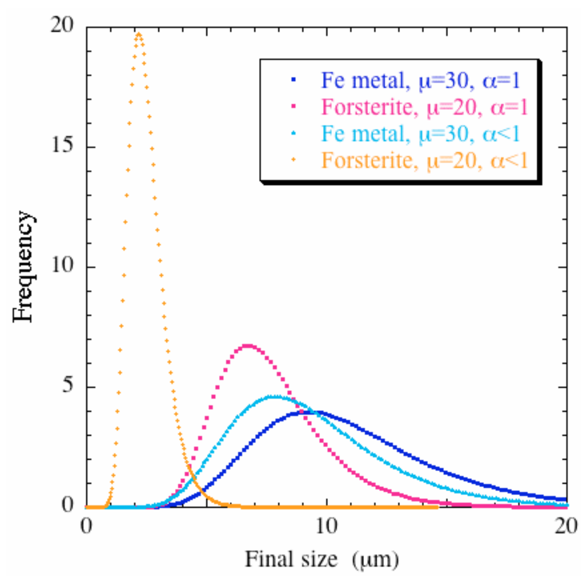

Fig. 2 Size distribution of dust grains condensed in the solar nebula at about 2A.U. $\Lambda = 10^6$.