

Condensation coefficients of metallic iron determined through condensation experiments

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Solid dust particles form by condensation of gaseous species in circumstellar environments or in protoplanetary disks. In order to estimate the timescale of formation of solids in such environments where the cooling time of gas varies largely depending on the environment, condensation coefficient, α (0-1), which is the ratio of atoms incorporating in a condensed phase to incident atoms, that is, condensation efficiency, should be known.

In this study, condensation coefficients of metallic iron have been estimated through condensation experiments. Iron is one of the most abundant metallic elements that condenses to metallic iron in stellar environments, of which gas species is Fe atom, and therefore is suitable for experimental and theoretical study due to its simple reaction.

Gaseous iron, produced by heating a metallic iron plate in a vacuum furnace at 1170 C, condenses on a molybdenum substrate set at distance of 1020, 900, 750, 600, or 415 C. The incident flux onto substrate is a function of heating temperature, size of iron plate, and distance from the gas source to the substrate. The weight changes of iron plate and substrate were measured and converted to evaporation and condensation rates, respectively. Condensates were observed with a FE-SEM, analyzed with EDS for chemical composition, and with EBSD for crystallinity and phase identification.

Condensates were identified to be crystalline metallic iron regardless of the condensation temperature and flux. The structure of the condensates varied with temperature of the substrate: At 415 C, loosely grown dendritic Fe metal covered the substrate and compactly packed Fe metal grew at 600, 750, 900, and 1020 C. The weight of condensate and source plate changes linearly with experimental duration.

Condensation coefficients obtained are 0.9-1.0 below 600 C, 0.7-0.8 at 750-900 C, and 0.9-1.0 at 1020 C, showing temperature dependence. Although the dependence of condensation coefficients on the degree of supersaturation is not clear, there appears to be positive correlation between the condensation flux and condensation coefficients for the experiments at 600 and 900 C.

The difference in values of condensation coefficients can be explained in terms of surface roughness of the condensates. Degree of roughness is related to the density of kink site, in which incoming atoms are incorporated as crystalline phase. On the surface with higher degree of roughness, condensation occurs efficiently because almost all incoming atoms can find kink sites before re-evaporation. In general, surface roughness increases as temperature increases or as condensation flux increases.

In the experiments, high values of condensation coefficients at high temperature may reflect the thermal roughening, whereas high values at low temperature come from kinetic roughening due to larger number of incoming atoms (high degree of supersaturation). The loosely grown dendritic structure observed in the experiments at 450 C is consistent with high values of condensation coefficients. Although all condensates at higher temperature show compact structure, difference in degree of roughness in the atomistic scale can exist and affects condensation efficiency. The positive correlation between the condensation flux and condensation coefficients is explained by an increase in surface roughness due to large condensation flux. Condensation flux is supposed to be related with supersaturation ratio. Condensation coefficient, as well as evaporation coefficient, has temperature and gas pressure dependence, suggesting an importance of experimental determination of those values. Estimation of dust formation time in stellar environments requires careful treatment on the condensation coefficients with respect to temperature and the degree of supersaturation of gas.