Geophysical Research Abstracts, Vol. 9, 05974, 2007
SRef-ID: 1607-7962/gra/EGU2007-A-05974

Evolution of forsterite and metallic iron dust in circumstellar discs

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Protoplanetary discs evolve through radial transfer, vertical movement, coagulation, and dstruction of dusts, which originated in previous molecular clouds. Recent astrnomical observation has showen the common occurrence of crystalline forsterite, enstatite, and amorphous silicate in protoplanetary discs with various sizes; T Tauri [1], Herbig Ae/Be [2], brown dwarfs [3], and proplyds in the Orion Nebula [4]. Although it is not clear whether the degree of crystallization has relevance to the disc evolution processes or not [5], it is likely that the silicate grains grow and crystallize even at the surface of discs, which may suggest turbulence in the nebula and easy crystallization. Another important observation is the finding of abundant crystalline forsterite in comets [e. g., 6,7] despite they are originated in the outer region of the solar system where amorphous silicates are thought to have survived stellar thermal processing. It is thus reasonable to consider the nucleation and growth of forsteirte along with metallic iron, the next abundant phase, during the evolution of a protoplanetary disc.

Condensation is a kinetic processes, of which rates are dependent on temperature, pressure, and gas composition. We investigate the evolution of forsterite and metallic iron dusts in a protoplanetary disc by using the model for grain formation by [9]. The growth rate of grains is determined 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 a parameter representing the surface energy relative to the thermal energy and a parameter representing the the saturation time scale relative to the collision time scale, in addition to the condensation coefficient. The average final size, size distribution, nucleation time, nucleation rate, and number density are examined. Physical parameters are surface tension of silicates (8.75x10^{-9} J m^{-2}), that of metallic iron (1.8x10^{-8} J m^{-2}), average solar abundance of elements, and cooling time scale (time to cool to 1/e of the initial temperature) of the solar nebula is 2x10^7 sec.

The condensation rate, J, is given by the Hertz-Knudsen equation , J = (alpha$_{cond}P$-alpha$_{evap}P_{eq}$)/(2π*mk*T)$^{1/2}$, which represents balance between forward and backward reactions in the kinetic theory of gas molecules. The parameter alpha$_{cond}$ is the condensation coefficient, alpha$_{evap}$ is the evaporation coefficient, $P$is the pressure, $P_{eq}$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. Although kinetic parameters alpha$_{cond}$ and alpha$_{evap}$ should be experimenteally determined, experimental difficulties prevent us from obtaining those parameters for a multi-element phases. Therefore, we use the condensation coefficient for metallic iron recently obtained [10] and evaporation coefficient in various P$_{H2}$ conditions [11] extrapolating to the condensation conditions.

The results show that the average grain size of metal is controlled principally by the cooling time scale of gas. It is, however, not the case for forsterite, of which grain size is dependent on the alpha. The size becomes smaller with decreasing coefficient, that is, increasing kinetic barrier for condensation. The metal grain is as large as several μm. On the other hand, forsterite grain size is largely dependent on alpha, and the size distribution is wide when alpha is 1, but is narrow when alpha $<$1. The size distribution of forsterite for alpha $<$1 is a few microns for most grains, which is consistent with astrophysical observation.

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