EVAPORATION OF ICY GRAINS IN NEBULAR SHOCKS. H. Miura[1], T. Yamamoto[2] and T. Nakamoto[3], [1]Department of Information and Biological Sciences, Nagoya City University, Yamanohata 1, Mizuho-cho, Mizuho-ku, Nagoya 467-8501, Japan (miurah@nsc.nagoya-cu.ac.jp), [2]Center for Planetary Science, Kobe University, 7-1-48, Minamimachi, Minatojima, Chuo-ku, Kobe 650-0047, Japan, [3]Department of Earth and Planetary Sciences, Tokyo Institute of Technology, 2-12-1, Ohokayama, Meguro-ku, Tokyo 152-8551, Japan.

Introduction: Gravitational collapse of a molecular cloud is a transient process to form protostars and protoplanetary disks. The infalling envelope onto the Keplerian disk often induces accretion shocks at their boundary. Recent ALMA observations suggested evaporation of icy grains at the shocked region [1,2]. According to the observations, some molecular species are enhanced at the radius of the centrifugal barrier. The icy grain evaporation would considerably affect the chemical environment of the nebula, however, the shock conditions for the icy grains to evaporate, such as shock velocity and gas number density, have not been investigated systematically.

In this study, we numerically simulated the shock heating and evaporation of icy grains in a wide range of the shock conditions that would be realized in the nebular environment.

Numerical Model: We adopt a two-step calculation method to obtain the detailed thermal history of icy grains behind a shock front. First we calculate the post-shock gas structure as a function of the distance from the shock front. Second we calculate the thermal evolution of icy grains using the post-shock gas structure obtained in the first step. We assume that the existance of icy grains does not affect the post-shock gas structure for simplicity. This post-processing scheme allows us to systematically investigate the shock condition for icy grain evaporation in a wide range of parameters efficiently.

Calculation of post-shock gas structure. We calculate the post-shock gas structure assuming optically-thin environment, namely, the thermal energy of the shocked gas can freely escape from the shocked region in the form of radiation. The shocked gas parameters just behind the shock front were determined by the Rankine-Hugoniot relation using the pre-shock parameters: a shock velocity and a pre-shock gas number density. The shocked gas is gradually cooled by line emissions from CO molecules and thermal collisions with non-evaporating sub-μm silicate grains. We focus weak shocks insufficient to evaporate H_2O icy grains, so the line cooling by H_2O molecules in gas phase was ignored. We consider a one-dimensional plane-parallel post-shock geometry, so the gas temperature and density are determined as a function of the distance from the shock front [e.g., 3].

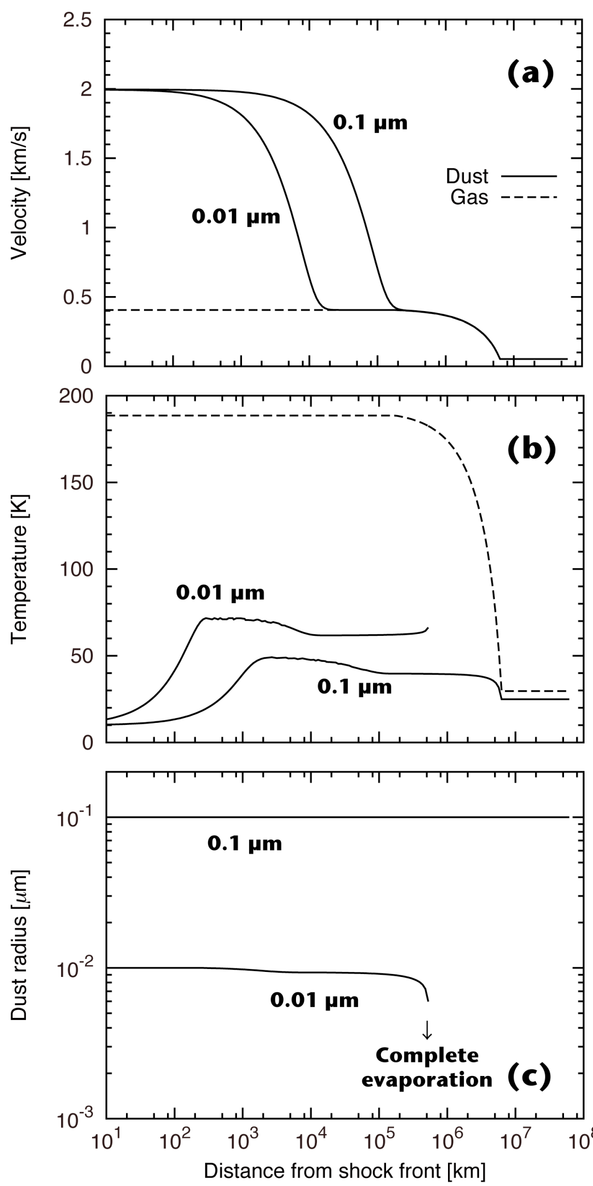

Fig. 1: Thermal evolution of an icy grain in the post-shock region. The shock velocity and the pre-shock gas number density are 2 km/s and 10^8 cm^{-3}, respectively. The grain is composed of CO_2. The results of two different initial radii are displayed by solid curves: 0.1 and 0.01 μm, respectively. The dashed curve shows the calculated result of the post-shock gas. (a) Dust and gas velocities with respect to the shock front. (b) Temperatures. (c) Dust radii.

Calculation of thermal evolution of icy grains. We suppose a spherical icy grain composed of a single component for simplicity. Some types of icy components were considered, such as, CO, CO_2, or H_2O. The evaporation rates of these icy grains were calculated by the Hertz-Knudsen equation, in which the equilibrium vapor pressure were adopted from literatures. The dependences of emissivity on the dust temperarture and the radius were taken into account [4]. We consider only the thermal evaporation as dust destuction processes. Other dust destruction process such as sputtering was not considered because of the small shock velocity considered in this study.

Results: In Fig. 1 we show an example of the calculated thermal evolution of icy grains. The given shock condition corresponds to a typical accretion shock suggested by ALMA observations [1,2]. This result shows that CO_2 icy grians with the radius of 0.1 μm hardly evaporate in the typical accretion shock, on the other hand, smaller CO_2 icy grains of 0.01 μm in radius evaporate completely. The smaller grain experiences higher temperature even in the same shock condition because of its smaller emissivity [4], however, it does not evaporate significantly before it stops against the shocked gas. The complete evaporation occurred far from the stopping distance, at which the icy grain is just exposed to the shocked (hot) gas without any relative motion. The shocked gas temperature is about 200 K, however, the icy grain temperature is about 80 K at most. The temperature difference is due to the insufficient thermal collisions with the rarefied shocked gas.

Fig. 2 shows the shock condition required for complete evaporation of icy grains when they are composed of only CO_2. Solid curves correspond to the minimal shock strength above which the CO_2 grains with radii of 1.0, 0.1, and 0.01 μm evaporate completely. It is found that larger grains require stronger shock for complete evaporation. The grayed region indicates a typical condition of accretion shocks. ALMA observations suggested that the gas number density in the shocked region is about 10^7 – 10^8 cm^{-3} [1]. The infall velocity, which gives the maximum shock velocity, is estimated about 2 - 3 km s^{-1} [1,2]. From Fig. 2, we found that the icy grains composed of CO_2 will evaporate completely if the size is about 0.01 μm or smaller. On the other hand, the grains larger than about 0.1 μm do not evaporate significantly in the typical accretion shocks.

Discussions: According to the recent ALMA observations, SO line emissions are enhanced at the radius of the centrifugal barrier, which was interpreted by desorption of SO from icy grain mantle due to accretion shocks [1]. We did not carry out the calculation of

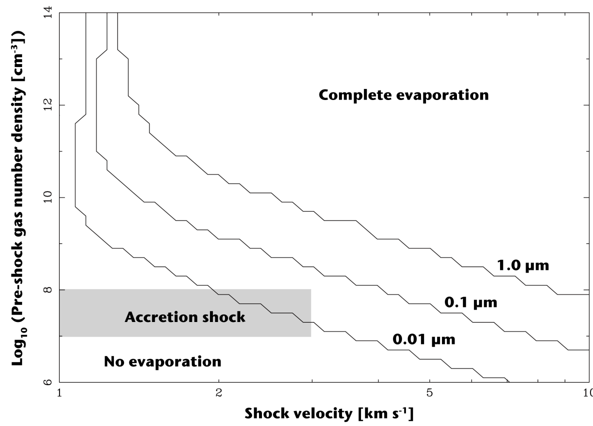

Fig. 2: Shock velocity and pre-shock gas number density required for complete evaporation of icy grains composed of CO_2. Larger grains require stronger shock condition for complete evaporation. The grayed region indicates a typical condition of accretion shocks obtained by ALMA observations.

the iced SO because of the lack of the equilibrium vapor pressure data, however, we can substitute the evaporation behaviour of CO_2 grains for iced SO because of similar desorption energies of these molecules [5]. Therefore, we can also infer the shock condition for evaporation of iced SO based on the shock diagram in Fig. 2. This suggests that the iced SO will not evaporate by the typical accuretion shock if the size exceeds about 0.1 μm, but will evaporate completely if the size is about 0.01 μm or smaller, indicating abundant 0.01 μm-sized iced SO in the infalling envelop.

Conclusions: We investigated shock conditions for icy grain evaporation in a wide range of parameters: shock velocity, pre-shock gas number density, and initial grain size. The gas density behind a typical accretion shock is so small that the icy grain temperature should be lower than the shocked gas temperature, so the gas temperature in the shocked region is not a direct information to judge the evaporation of icy grains. The grain-size dependence of the minimal shock criteria for complete evaporation was clarified on the shock diagram. The shock heating by the typical accretion shock is sufficient to evaporate about 0.01 μm-sized icy grains composed of CO_2 or other volatiles showing the similar evaporation behaviour.

References: [1] Sakai N. et al. (2014) *Nature, 507,* 78–80. [2] Yen H.-W. et al. (2014) *ApJ, 793,* 1 (20pp). [3] Miura H. and Nakamoto T. (2006) *ApJ, 651,* 1272–1295. [4] Kobayashi H. et al. (2008) Icarus*, 195,* 871–881. [5] The UMIST Database for Astrochemistry, http://www.udfa.ajmarkwick.net