FORMATION OF ROCKY AND ICY PLANETESIMALS INSIDE AND OUTSIDE THE SNOW LINE. R. Hyodo[1,2], S. Ida[2], S. Charnoz[3], [1]ISAS, JAXA (hyodo.ryuki@jaxa.jp), [2]Earth-Life Science Institute, Tokyo Institute of Technology, [3]Institut de Physique du Globe de Paris, Université Paris Diderot, Université Sorbonne Paris Cité, CNRS UMR.

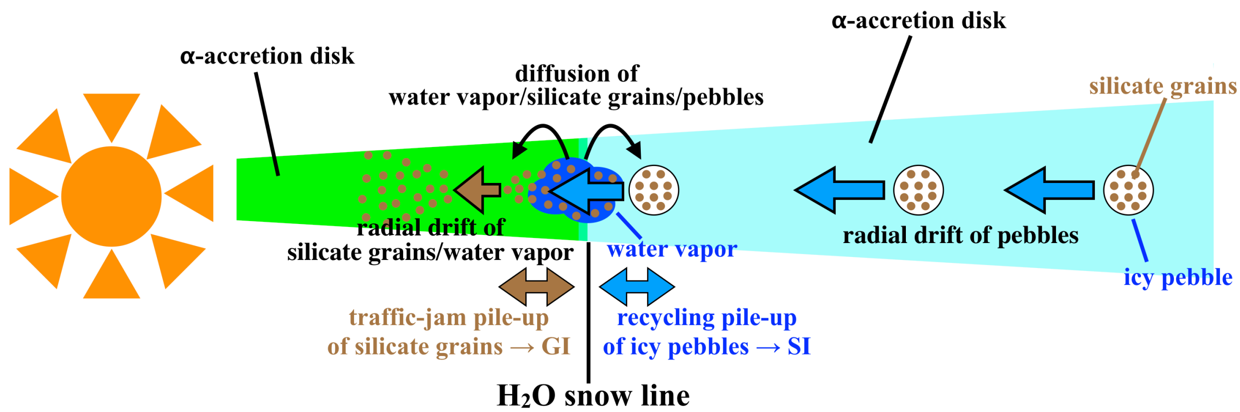

Figure 1: Schematic figure of our numerical approaches and pile-up of solids inside/outside the snow line. Using a local one-dimensional code, we solved the radial drift and the turbulent diffusion of pebbles/silicate grains/water vapor, taking account of their sublimation/condensation around the snow line [7]. An icy pebble is modeled to contain micron-sized silicate grains that are uniformly mixed with ice and are released during the ice sublimation. Recycling of water vapor due to outward radial diffusion beyond the snow line and its condensation cause a high enough mid-plane solid-to-gas ratio for SI of pebbles beyond the snow line. Silicate grains released by sublimation of icy pebbles pile up just inside the snow line due to "traffic jam" effect (which potentially triggers GI): silicate grains are well coupled to the gas and they drift much slower than pebbles.

Introduction: Planetesimals, sub-km to several-hundred-km, are the fundamental building blocks of planets and small bodies. It is still unclear how planetesimals are formed from small dusts and/or pebbles. Streaming instability (SI) is a possible mechanism that produce planetesimals, but it requires special local conditions such as a high solid-to-gas ratio ($Z > 1$) for sufficiently large pebbles (the Stokes number $St > 0.01$) [e.g. 1,2,3]. Gravitational instability (GI) is another possible mechanism to form planetesimals triggered by pile-up of solids in a runaway fashion [e.g. 4].

In previous works, many authors discussed that the region outside the water snow line is a favorable location for SI because water vapor released inside the snow line diffuses outward and then re-condenses outside the snow line [e.g. 5,6]. In contrast, few studies focused on the pile-up of silicate grains inside the snow line [e.g. 4]. Even though these previous works investigated processes around the snow line, they have different settings and models and thus further studies are required. Here, we wish to understand how local runaway pile-up of solids (silicate and water ice) occurs inside or outside the snow line [7].

Numerical methods: We assume an icy pebble contains micron-sized silicate grains that are uniformly mixed with ice and are released during the ice sublimation. Using a local one-dimensional code, we solve the radial drift and the turbulent diffusion of solids and the water vapor, taking account of their sublimation and condensation around the snow line (Figure 1). We consider the following back-reactions of solids to gas: (1) the radial drift of solids become slower for larger solid-to-gas ratio, Z and (2) diffusion of solids becomes weaker for larger solid-to-gas ratio, that is, its diffusivity is written as $D=D_0/(1+Z)^K$, where D_0 is the diffusivity of solid at K=0 (no back-reaction) and K is the coefficient. Scale height evolution of the released silicate particles is considered. We use different effective viscous parameters between those for turbulent diffusion (α_{tur}) and those for the gas accretion rate onto the central star (α_{acc}). We also studied the dependence on the ratio of the solid mass flux to the gas ($F_{p/g}$). More detailed descriptions are found in Hyodo et al. (2019) [7].

Results: We show that the favorable locations for the pile-up of silicate grains and icy pebbles are the regions in the proximity of the water snow line inside and outside it, respectively (Figure 2) [7]. We found that runaway pile-ups occur when both the back-reactions for radial drift and diffusion are included (K=1 or 2 cases). In the case with only the back-reaction for the radial drift (K=0 case), no runaway pile-up is found except for extremely high pebble flux, while the condition of streaming instability can be satisfied for relatively large $F_{p/g}$ as found in the past literatures (K=0 case in Figure 2). If the back-reactions for radial diffusion is considered, the runaway pile-up occurs for reasonable value of pebble flux (K=1 or 2 in Figure 2). The runaway pile-up of silicate grains that would lead to formation of rocky planetesimals occurs for $\alpha_{tur} \ll \alpha_{acc}$, while the runaway pile-up of icy pebbles is favored for $\alpha_{tur} \sim \alpha_{acc}$ (see Figure 2).

Conclusion: The back-reactions of solids in radial diffusion ($K\neq0$ case) play critical roles on the runaway pile-up of silicate grains and icy pebbles inside and outside the snow line. Both inside and outside the snow line, solids can pile up significantly under the reasonable conditions (Figure 2), which would lead to formation of rocky/dry and icy/wet either planetesimals inside and outside of the snow line, respectively.

References: [1] Youdin, A. N., and Lithwick, Y. (2007) *Icarus*, 192, 588. [2] Johansen, A. et al. (2009) *ApJ*, 704, L75. [3] Carrera, D. et al. (2015) *A&A*, 579, A43. [4] Ida, S. and Guillot, T. (2016) *A&A*, 596, L3. [5] Schoonenberg, D. and Ormel, C. W. (2017) *A&A*, 602, A21. [6] Drazkowska, J. and Alibert, Y. (2017) *A&A*, 608, A92. [7] Hyodo et al. (2019) *A&A*, A90, 13.

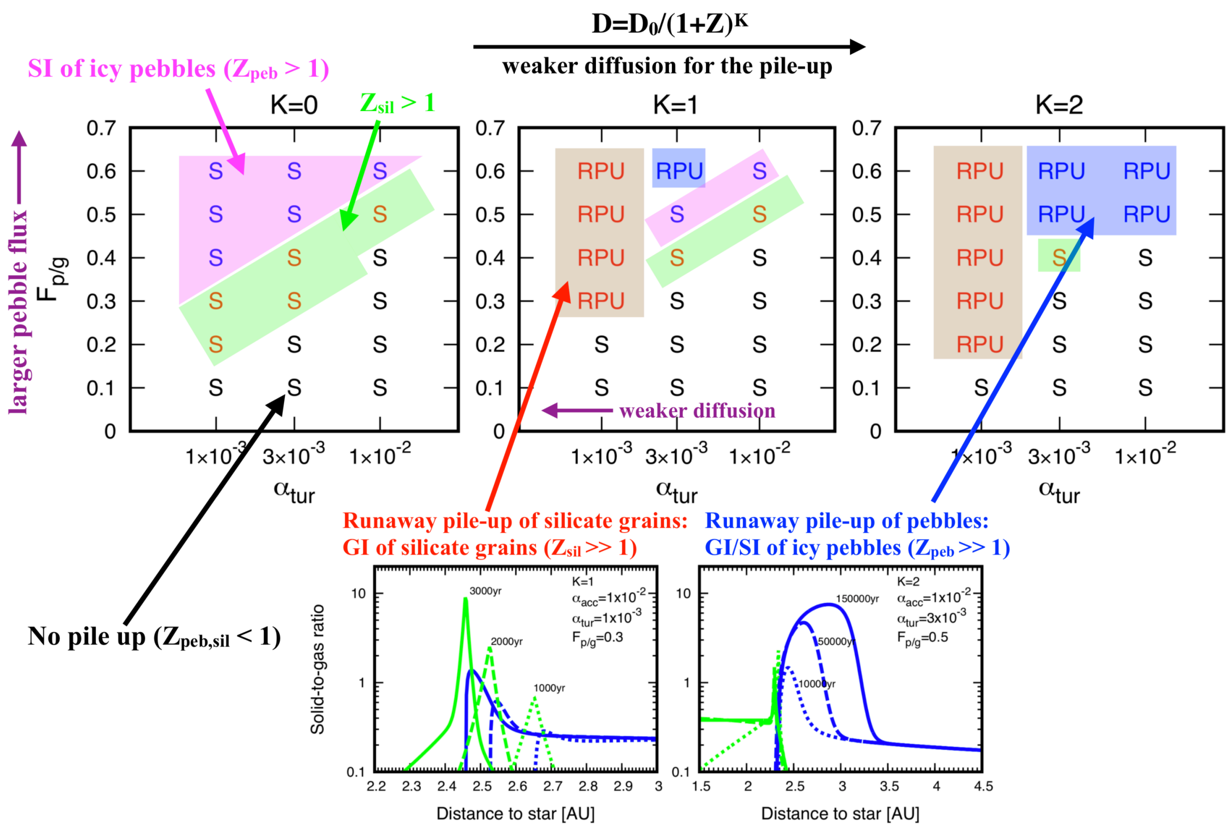

Figure 2. Parameter maps where either silicate grains' runaway pile-ups (labeled "RPU" in red color), icy pebble runaway pile-ups (labeled "RPU" in blue color) or steady state without runaway pile-ups (labeled "S") occurs for different α_{tur} and $F_{p/g}$ ($\alpha_{acc} = 10^{-2}$). If the midplane dust-to-gas ratio of silicate grains is larger than unity for the case of "S", the label is highlighted in red color. If the midplane dust-to-gas ratios of pebbles as well as those of silicate grains are larger than unity for the case of "S", the label is highlighted in blue color. From left to right panels, cases of K=0, 1, and 2 are shown, respectively. Two additional panels are shown at the bottom as examples of silicate grains' runaway pile-up and pebbles' runaway pile-up, respectively. The original figures are found in Hyodo et al. (2019) [7].