Effects of Icy Dust Particles on the Location of the Snowline in Protoplanetary Disks. A. Oka[1], T. Nakamoto[1], M. Ikoma[1], and S. Ida[1], [1]Department of Earth and Planetary Sciences, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8551, Japan; akinori@geo.titech.ac.jp

Introduction: The snowline in a protoplanetary disk is the boundary exterior to which water ice condenses. Because the temperature in a protoplanetary disk decreases with distance from the central star, water molecules in the outer region of the disk condenses to ice while those in the inner region of the disk are vapor. The snowline plays a very important role on the formation of the planets, because the amount of the solid materials changes drastically with crossing the snowline.

In the early phase of the disk evolution before the formation of planetesimals, the disk is thought to be optically thick due to a large number of small dust particles. In such an optically thick disk, the snowline migrates inward during the evolution of the disk because the optical property of the disk changes and the viscous dissipation becomes inefficient [1, 2]. However, in the previous works only silicate dust particles were taken into account as the opacity source even in the region outside the snowline where icy particles also contribute to the opacity. In this study we obtain the location of the snowline in an optically thick protoplanetary disk with a two-dust model, which considers opacity by silicate and ice particles, and examine the evolution of the snowline during the evolution of the disk. And we compare the result with that with single dust model which considers opacity only by silicate dust particles.

Model: *The disk structure.* We consider an optically thick accretion disk around a T Tauri star. The steady state accretion is assumed. The effective temperature, the radius, and the mass of the central star are set to be 3000K, twice the solar radius, and a half of the solar mass, respectively. Then the energy sources in the disk are the irradiation by the central star and the viscous dissipation. We evaluate the viscosity with the alpha-prescription by Shakura and Sunyaev [3] and the value of alpha is set to be 0.01. The energy transfer is dominated by the radiation transfer so we determine the temperature of the disk with the radiative equilibrium. Opacity comes from silicate and icy particles. It is assumed that sizes of dust particles are 0.1 μm and dust particles are completely mixed with gas. Absorption coefficients and gas-to-dust mass ratio are taken from Miyake and Nakagawa [4]. We consider only absorption of radiation by dust particles and ignore scattering. The condensation of ice is determined by the saturated vapor pressure of water.

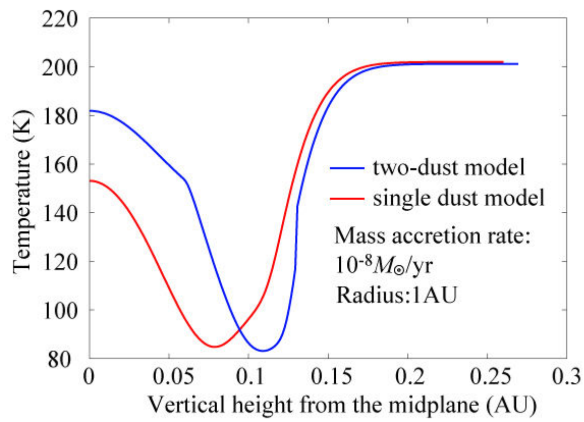

Figure 1: Temperature profile in the vertical direction at radius of 1AU. Blue curve shows the temperature profile for the two-dust model and red curve shows that for the single dust model.

The disk evolution. To know the migration of the snowline, we simulate the disk's thermal structure for different disk-accretion rates instead of integrating time-dependent equations for the disk evolution. The viscosity in the disk is the same as in the disk structure.

Method: To obtain the structure of the disk we employ the 1-D plane-parallel radiative transfer method in Dullemond *et al.* [5]. We modify it to take into account the viscous heating and the opacity by icy dust particles. The viscosity coefficient of the disk is consistently evaluated using the disk temperature and density structure.

Results: *Temperature profile in the vertical direction.* Figure 1 shows the temperature profile in vertical direction at radius of 1AU with the accretion rate of 10^{-8} M_{sun}/yr. Blue curve shows the temperature profile for the two-dust model (silicate and icy particles), while red curve shows that only with silicate particles. One can see that the temperature near the midplane in the two-dust model case is higher than that of the no ice case. This is because the optical depth in the vertical direction of the two-dust model case is larger than that of the no ice case so the thermal energy produced by viscous dissipation near the midplane cannot escape efficiently through radiative energy transfer in the vertical direction in the two-dust model case.

The location of the snowline. Figure 2 shows the location of the snowline in the 2-D sectional view. The accretion rate of this case is $10^{-8} M_{sun}$/yr. In the blue colored region ice condenses. Red curve shows the location where the optical thickness for the radiation from the central star becomes unity. Green curve shows the scale height of the disk. One can see that the snowline has a two-branched structure as Davis [2] pointed out. The innermost lower snowline is caused by the viscous dissipation. The upper branch of the snowline is caused by the irradiation heating and by the low gas density of the disk. The dotted curve shows the snowline calculated only with silicate particles. It is located closer to the central star at the midplane than that with the two-dust model. This is because the ice condensing layer locates at intermediate vertical height at around R=1AU with the two-dust model and it causes an additional optical thickness so the thermal energy produced by the viscous dissipation near the midplane cannot escape in the vertical direction efficiently.

Migration of the snowline. Figure 3 shows the migration of the snowline at the midplane of the disk with the disk evolution. The horizontal axis shows the disk accretion rate and the vertical axis shows the distance of the snowline from the central star. A decrease of the accretion rate represents the disk evolution. The location of the snowline with two-dust model is always about 1.3 times more distant from the central star than that with single dust model and migrates inward from 3.7AU to 0.5AU as the accretion rate of the disk decreases from $10^{-7} M_{sun}$/yr to $10^{-9} M_{sun}$/yr.

Conclusion: In this work we examined the location of the snowline in a protoplanetary disk around a T Tauri star. The disk is considered to be an accretion disk. The dust model producing the opacity includes two kinds of dust particles, silicate particles and ice particles. What we have found are as follows:

1. Vertical temperature profile of the disk with two-dust model is different from that of the single-dust model (Figure 1). This is because the optical depth with the two-dust model is larger than that of the single-dust model.
2. The location of the snowline is more distant from the central star with the two-dust model than that of the single-dust model (Figure 2). This is because the large optical depth reduces the efficiency of the radiation energy transfer.
3. The snowline with two-dust model locates about 1.3 times more distant than that with single dust model and migrates inward from 3.7 AU to 0.5AU as the accretion rate of the disk decreases from $10^{-7} M_{sun}$/yr to $10^{-9} M_{sun}$/yr (Figure 3).

References: [1] Garaud, P. and Lin, D. N. C. (2007) *ApJ* **654**, 606-624. [2] Davis, S. S. (2005) *ApJ* **620**, 994-1001. [3] Shakura, N. I. and Sunyaev, R. A. (1973) *A&A* **24**, 337-355. [4] Miyake, K. and Nakagawa, Y. (1993) *Icarus* **106**, 20. [5] Dullemond, C. *et al.* (2002) *A&A* **389**, 464-474.

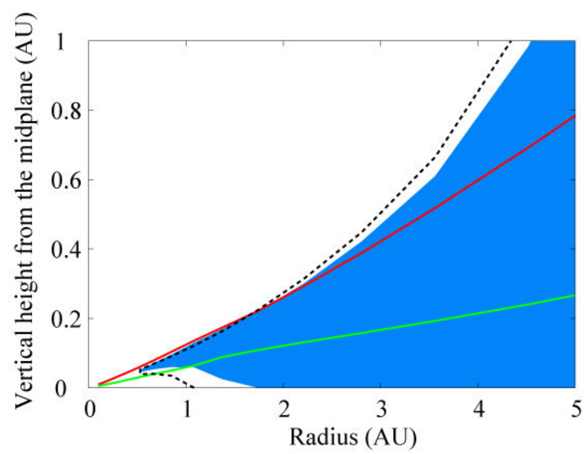

Figure 2: Ice-condensing region with the accretion rate of $10^{-8} M_{sun}$/yr. Blue-colored region shows the ice-condensing region. Red curve shows the location where the radiation from the central star is mostly absorbed by the disk. Green curve shows the scale height of the disk. The dotted curve shows the snowline for the single dust model.

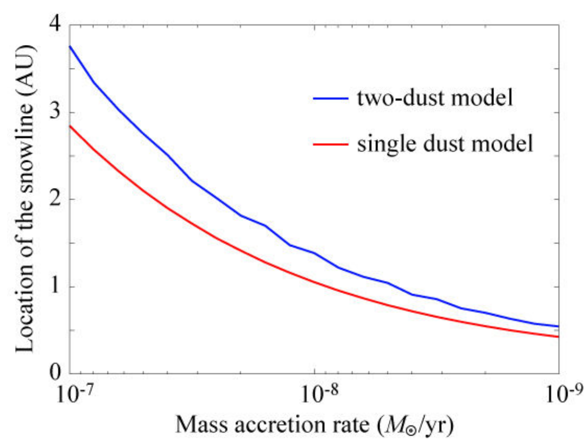

Figure 3: The evolution of the snowline at the midplane with the accretion rate of the disk. Blue curve shows the location of the snowline for the two-dust model and red curve shows that for the single dust model.