Evolution of the snow line in magnetohydrodynamically accreting protoplanetary disks: an analysis using a consistent dust model

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The orbit where ices evaporate in protoplanetary disks is called the snow line. In general, the snow line location moves with the evolution of the central star and the disks. If we can understand how the snow line moves, it will help us understand how the Earth and other rocky planets formed.
In this study, we focus on the temperature structure of accretion disks and the snow line migration by the interaction of magnetic field and gas. Recent magnetohydrodynamic (MHD) simulations have shown that accretion heating is inefficient in magnetically accreting disks. Mori et al. (2021) constructed a simulation-based model of disk temperature evolution and showed that the snowline reaches 1 au at an early stage of disk evolution. However, they used dust with a size of 0.1 μm in the calculation of the cooling efficiency and the ionization structure of the disks. Therefore, it was not possible to investigate consistently how the temperature structure of the disks and the snow line moves with the evolution of the size distribution due to dust growth.
In this study, we introduce a consistent dust model into the MHD model for disk temperature structure, and calculate change of the disk temperature distribution with the change of the dust size distribution. The dust size distribution is assumed to follow a power law, with the maximum dust size as a parameter. We find that when the maximum dust size is less than 100 μm, the temperature of the disks increases with the growth of the dust because of the effect of the increase in the ionization degree. On the other hand, when the maximum size of the dust is larger than 100 μm, the effect of the decrease in the dust opacity exceeds the effect of the increase in the ionization degree, and thus the disk temperature decreases with the growth of the dust. Therefore, the disks heat up most efficiently when the maximum dust size is about 100 μm. The results show that the snow line reaches the orbit of 1 au within 0.65 Myr after disk formation when the dust size is about 0.1 μm, while the arrival time is delayed to 2.2 Myr when the maximum dust size is 100 μm.
This study shows that the contribution of accretion heating cannot be neglected even in MHD disks depending on the dust size distribution. It is also suggested that protoplanets born in 1 au may evolve into rocky planets like the Earth if the heating efficiency of the disks is maximized (i.e., if the maximum dust size is about 100 μm). In the future, we plan to incorporate the temporal evolution of the size distribution into our disk temperature model to clarify when and where the Earth formed.

Keywords: protoplanetary disks, magnetohydrodynamic (MHD), accretion, snow line, planet formation

