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Evolution of the Ice Boundary in Optically Thick Protoplanetary Disks

Akinori Oka[1]; Masahiro Ikoma[2]; Taishi Nakamoto[3]; Shigeru Ida[4]

[1] Earth and Planetary sciences, Tokyo tech; [2] Earth Planet. Sci.
Tokyo Tech.; [3] Tokyo Tech; [4] Dept. of Earth and Planetary Sci., Tokyo Inst. of Tech.

An ice-condensed region in a protoplanetary disk plays an important role in the planet formation process. Icy bodies in the region may promote the formation of the massive cores of giant planets and/or may supply water to Earth. Since protoplanetary disks contain large amount of water, the solid mass surface density increases several times once water ice condenses. It is thought that the cores of gas giants form in the ice-condensed region, since the formation of the cores require large solid mass surface density. On the origin of water of the Earth, it is thought that the amount of water supplied from the protoplanetary disk gas in vapor phase is not enough, so some researchers think that the icy bodies in the ice-condensed region may be the origin of water of the Earth. The heating source of protoplanetary disks is mainly the stellar irradiation and the viscous dissipation due to the differential rotation of the disk. Since they are more effective in the inner region of the disk, the temperature of the inner region becomes so high that ice does not condense, whereas the temperature of the outer region of the disk is so low that ice condenses. The boundary between the two regions is called the ice boundary. The temperature distribution in the disk is determined by the heating rate, the cooling rate, and the optical property of the disk. As the disk evolves, i.e., the surface density decreases, the viscous dissipation decays and the optical property of the disk changes. Then the temperature distribution in the disk changes and the location of the ice boundary migrates. In this study, we examined the temperature and the density distributions in an optically thick protoplanetary disk around a T Tauri star and numeriacally simulated the migration of the ice boundary.

We calculated the disk evolution with the standard disk accretion model and employed the alpha-prescription for viscosity. Sound speed and pressure scale height were calculated from the disk structure. The viscous dissipation and the stellar irradiation were considered as the heating source. The disk was assumed to be optically thick in the radial direction and the temperature distribution was calculated by solving the one-dimensional radiative transfer in the vertical direction. 0.1 micron-sized dust particles were considered for the opacity source and assumed to be well mixed with the gas. The disk's vertical density profile was calculated with the assumption of the vertical hydrostatic equilibrium. The condition of the condensation of ice was given by the saturated vapor pressure curve. To solve the radiative transfer, we used a method described in Dullemond et al. (2002); we numerically calculated the radiative transfer equation for all the frequencies and all the directions under the assumption of the plane parallel geometry.

As a result, we have found that the ice boundary migrates from ~10AU to ~1AU as the disk evolves. This is because the temperature of the disk decreases as the disk evolves. The disk evolution, i.e., the decrement of the surface density leads to the decrement of viscous dissipation. At the same time, the decrement of surface density causes the enhancement of radiative cooling. Therefore, the temeperature of the disk decreases. Davis (2005) carried out similar calculations employing the beta-prescription for the viscosity, and we found that his results are qualitatively similar to ours.

In this study, we examined the location of ice boundary in the optically thick protoplanetary disk. However, when we consider the formation of cores of massive planets and the chemical composition of planetesimals, we have to investigate the evolution of the disk until it becomes optically thin. That is the future work.