Accretion of icy pebbles by rocky planetary embryos in cooling protoplanetary disks

Takao Sato[1], *Satoshi Okuzumi[1], Shigeru Ida[2]

1.Department of Earth and Planetary Sciences, Tokyo Institute of Technology, 2.Earth-Life Science Institute, Tokyo Institute of Technology

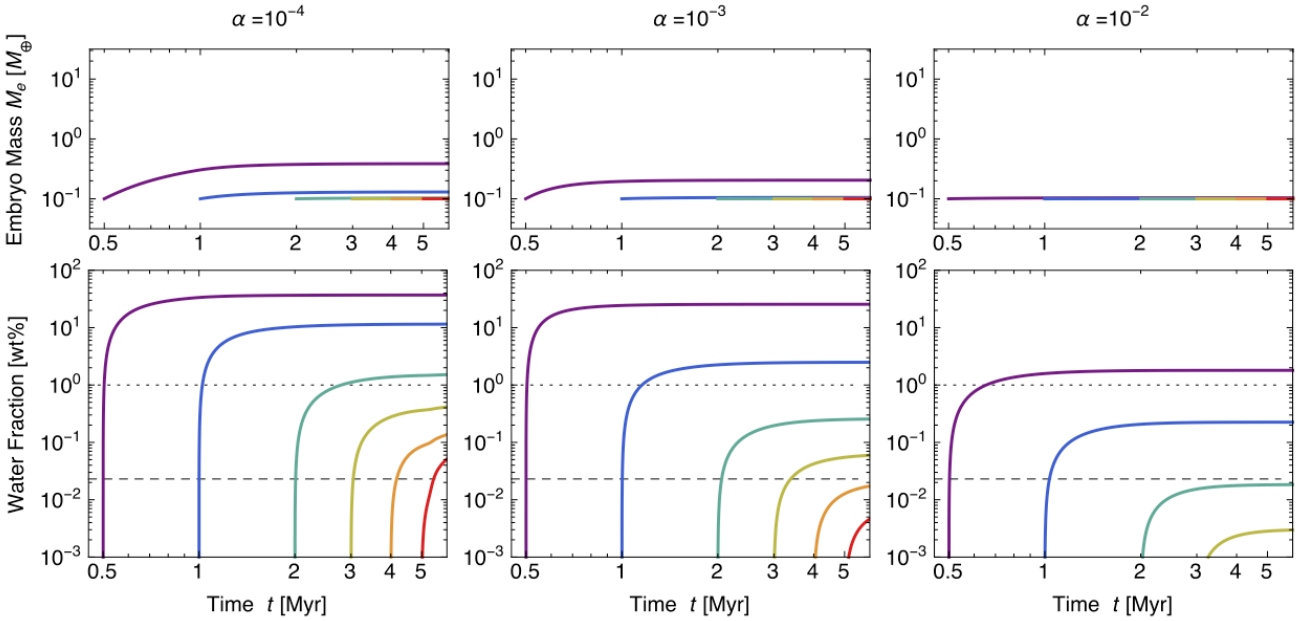
Standard accretion disk models suggest that the snow line in the solar nebula migrated interior to the Earth's orbit in a late stage of nebula evolution. In this late stage, a significant amount of ice could have been delivered to 1 AU from the outer regions of the disk in the form of mm to dm-sized icy particles called "pebbles." This raises the question as to why the present Earth is so depleted of water.

In this study, we quantify the amount of icy pebbles accreted by terrestrial embryos in a cooling protoplanetary disk assuming that no mechanism halts the pebble flow outside the terrestrial planet forming region. We use a simplified version of the coagulation equation to calculate the formation and radial inward drift of icy pebbles in a protoplanetary disk. The pebble accretion cross section of an embryo is calculated using analytic expressions presented by recent studies. We find that the final mass and water content of terrestrial embryos strongly depends on the radial extent of the gas disk, the strength of disk turbulence, and the time at which the snow lines arrives at 1 AU. The disk's radial extent sets the lifetime of the pebble flow, while turbulence determines the density of pebbles at the midplane where the embryos reside. We find that the final water mass fraction of the embryos falls below that of the present Earth (0.023 wt%) only if the disk's radial extent is 100 AU or less, turbulence is strong at 1 AU, and the snow line arrives at 1 AU later than 2-4 Myr after disk formation. If the solar nebula extended to 300 AU, initially rocky embryos would have evolved into icy planets of 1-10 Earth masses unless the snow-line migration was slow. If the proto-Earth contained water of ~ 1 wt% as might be suggested by the density deficit of the Earth's outer core, it would have been possible for the proto-Earth to form with weaker turbulence and with earlier (> 0.5-2 Myr) snow-line migration.

Reference: Sato, T., Okuzumi, S., & Ida, S. 2016, A&A, in press (arXiv:1512.02414)

Figure: Time evolution of the mass and water fraction of an initially purely rocky embryo of the initial mass of 0.1 Earth mass placed at 1 AU in a cooling protoplanetary disk with the outermost radius of 100 AU. The curves show how the mass and water fraction evolve with time if the snow line reaches 1 AU at different times (0.5, 1, 2, 3, 4, and 5 Myr from left to right) after disk formation. The dashed and dotted lines mark the water fraction of 0.023 wt% (corresponding to the current terrestrial value estimated from the ocean mass) and 1 wt% (a theoretical upper limit on the primordial terrestrial value estimated from the mass deficit of the outer core), respectively. The left, center, and right panels are for turbulence parameters of 10^{-4}, 10^{-3}, 10^{-2}, respectively.

Keywords: snow line, terrestrial planets, water


α =10^−4
α =10^−3
α =10^−2
Embryo Mass M_e [M_⊕]
Water Fraction [wt%]
Time t [Myr]
Time t [Myr]
Time t [Myr]