Delivery of ammonia ice to Ceres by pebble accretion

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Ceres is the largest asteroid in the solar system, comprising almost one-third of the total mass of the asteroid belt. The spectrometer onboard the Dawn spacecraft revealed the presence of ammoniated phyllosilicates across the surface of Ceres (De Sanctis et al. 2015), suggesting that Ceres contained ammonia when it differentiated. However, ammonia alone is unstable on the surface of present-day Ceres, where the maximum temperature (≈ 240 K) is well above the sublimation temperature of ammonia ice. This could imply that Ceres was born in the cold outer part of the solar nebula and subsequently migrated to the current orbit. Another possibility is that Ceres formed in situ but the solar nebula was cold enough to preserve ammonia ice even at the current orbit of Ceres.

In this study, we examine the latter scenario by quantifying how much ammonia ice could have been delivered to Ceres in the solar nebula. We use a standard viscous accretion disk model to infer how the temperature of the solar nebula decreased with time. We also simulate the coagulation, radial inward drift, and sublimation of ammonia-bearing icy particles in the background gas disk to compute the radial mass flux of the particles at 3 au as a function of time. The mass flux is then converted into the accretion rate of ammonia-bearing ice by Ceres and smaller asteroids using the state-of-the-art analytic formula for pebble accretion (Visser & Ormel 2016).

We find that the thickness of the ammonia-bearing ice layer forming on Ceres depends significantly on the initial mass $M_{\rm disk}$ and dimensionless viscosity parameter α of the solar nebula. A layer thick enough to globally cover the surface of Ceres forms when $M_{\rm disk} < 10^{-2} M_\odot$ and $\alpha > 10^{-3}$. Our results thus provide unique constraints on the fundamental parameters of the protoplanetary disk that formed the solar system. We also find that the layer thickness is highly sensitive to the initial asteroid mass, possibly explaining why ammoniated phyllosilicates are observed in the largest asteroid Ceres.