Evolution of thermal and internal structures of medium/small sized icy bodies: conditions for the formation and duration of the subsurface ocean

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Subsurface oceans are likely exist in several icy bodies basically due to heat from the rocky core. The existence of ocean is notable in terms of astrobiology as another type of habitable environment independent of sunlight, which is different from that on the surface of the terrestrial planets. Previous measurements by spacecrafts of induced magnetic fields, tidal interactions (Tidal Love number) and libration, and telescopic observations oscillations of auroras have suggested to exist the subsurface ocean in several moons in the Jovian and Saturnian systems. On the other hand, the Uranian or Neptunian moons are lack of observation data and thus possibility of the ocean are unclear. Although many theoretical calculations have been performed to estimate current interior state including the likelihood of the ocean, they are not well convinced because equilibrium state and/or only conduction as a heat transport process are assumed.

We perform numerical simulations for a long-term thermal evolution with various surface radii from 200 to 1000 km and bulk densities from 1.125 to 2.5 g/cc. Solving the one-dimensional spherically symmetric heat transport equation including effects of conduction and convection using the mixing length theory for viscous fluids provides temporal change of the interior thermal structure and the thickness of subsurface ocean. Internal structure is assumed to be completely differentiated into two layers: central rocky core and overlying H_2O layer. The H_2O layer is completely solid state in initial and then it changes the state between solid and liquid according to the temperature change. We consider decay heat of long-lived radioactive isotopes in the rocky core as an unique heat source, which are assumed to be in the CI chondritic concentrations. Because efficiency of the convective heat transfer of the solid ice shell strongly depends on the ice viscosity which is poorly understood, we set the melting point viscosity in the range of 10^{13}-10^{17} Pas as a parameter, which reflects the grain size of terrestrial ice near the melting point. The surface temperature is fixed over the time and various values from 50 to 130 K are assumed. In addition, we consider various amount of ammonia as an anti-freeze compound in the H_2O layer.

For icy bodies with the same bulk density, the larger surface radius is more likely to sustain the subsurface ocean due to the larger rocky core (larger amount of the heat source). For example, the icy body with the bulk density of 1.5 g/cc and the surface radius of 400 km never have the subsurface ocean. On the other hand, the icy body with that of 800 km should have the subsurface ocean from 4.56 to 0.95 Gyrs ago. And, the body with that of 1000 km, the subsurface ocean exists until present. For the same surface radius, larger bulk density is likely to sustain the ocean because of the larger rocky core and thus larger amount of heat generation. On the other hand, smaller amount of H_2O layer tends to completely solidify the ocean. For example, in case that a surface radius is 800 km and the bulk density of 1.125, 1.25 and 2.00 g/cc, the ocean will sustain for 3.59, 3.64 and 2.94 Gyrs, respectively. Larger melting point viscosity of the ice suppresses icy convection and the more likely the subsurface ocean is to survive. More interestingly, lower surface temperature results in a longer lifetime of the ocean. This is because the lower surface temperature increases the viscosity of the ice, which in turn suppress the icy convection and the heat transport through the ice shell. Presence of ammonia in the H_2O layer also prolongs the duration of the subsurface ocean because the freezing point of H_2O is lowered by up to 100 K.

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