Stability of subsurface ocean of Pluto

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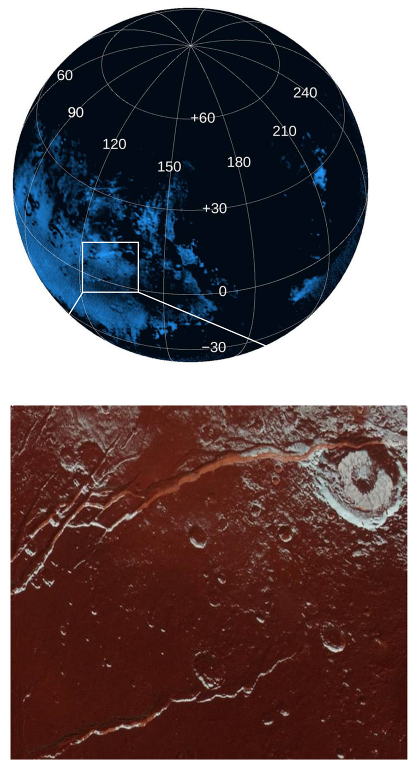
Introduction and scope: Signatures for subsurface ocean in Pluto

- Mean surface radius=1188.3 km, Bulk density=1.88 g/cc (indicating 30-35 wt% of H_2O)
- No detectable flattening implies warm/deformable interior (ocean?) [1]
- Reorientation indicates that the ocean currently exists [2]
- Extensional tectonics with strong H_2O spectral signature [3, 4]

Astrobiological/geophysical interests to investigate the conditions which Pluto may retain an ocean.

- Former numerical work for the Pluto's ocean [5] considers only a fixed water-rock ratio (only ice-Ih appeared case) and an initially frozen state.

What we did? Further numerical investigations under various parameters for,
- various water/rock volume ratio
- radioisotope abundances (CI chondritic/ordinary chindritic)
- ice reference viscosity
- initial thermal state (entirely frozen/molten water layer)



Map showing the correlation between LEISA spectrum and a template H_2O ice spectrum [3]

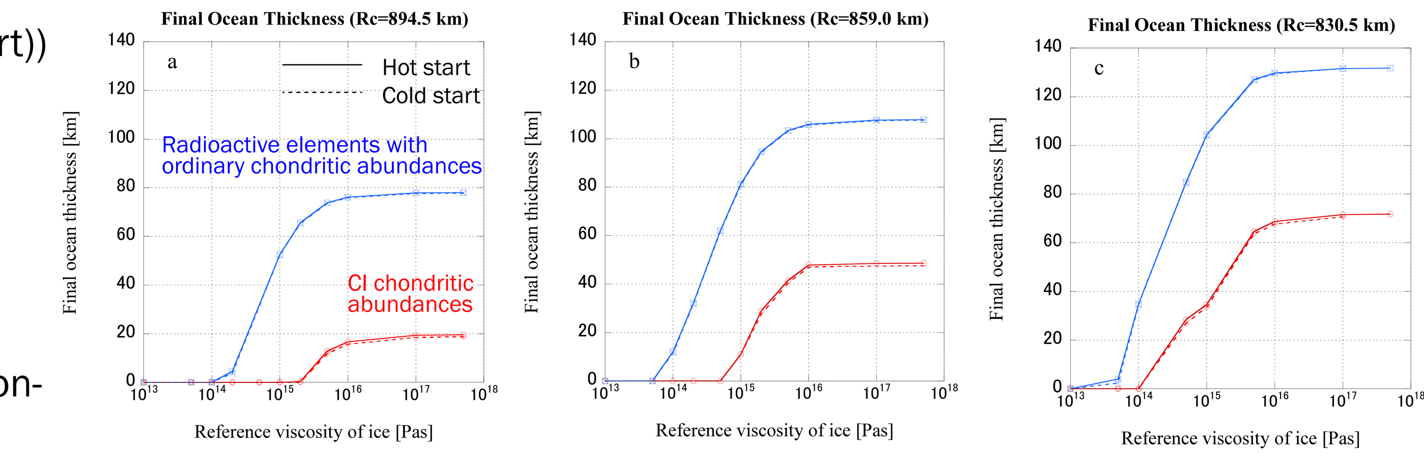
1-minute summary

We investigated stability of the Pluto's ocean with variations of:
- Water-rock volume ratio (core size; small/medium/large)
- Radioactive isotope abundances (CI/Ordinary chondritic)
- Initial state of water layer (entirely molten (hot start) / frozen (cold start))
- Ice reference viscosity ($1x10^{13}$ - $5x10^{17}$ Pas)

We've got results as follows:
- Large ice viscosity leads thicker ocean.
- Ordinary chondritic abundances lead thicker ocean.
- Smaller core leads thicker ocean.
- Initial state does not affect the current ocean thickness.
- Present Pluto may have a subsurface ocean if the ice shell is purely conductive or only weakly convective, and its thickness is largely uncertain and could be 20–130 km, depending on the ice reference viscosity.

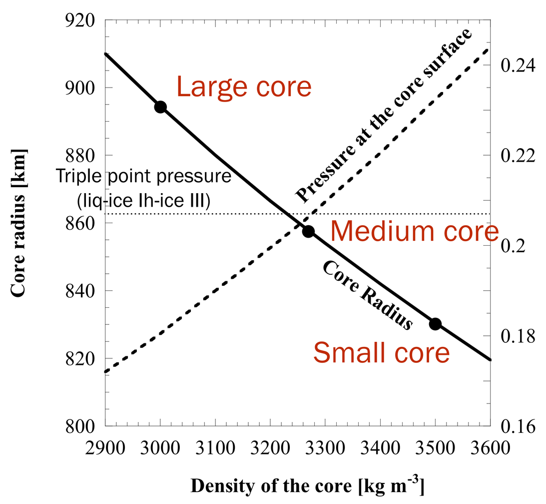
Final thickness of the subsurface ocean as a function of the ice reference viscosity for three core sizes.

Large core / Medium core / Small core



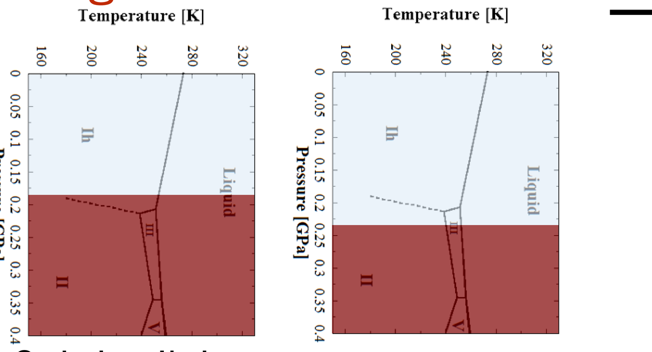
Our interior model and case studies

Assumption: 2-components, water (1.0 g/cc) and rock (3.0-3.5 g/cc), are completely differentiated in initial.

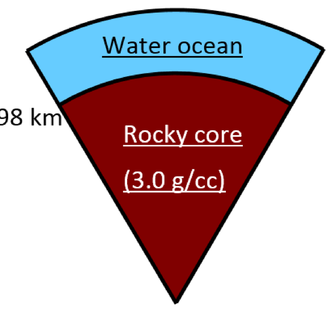
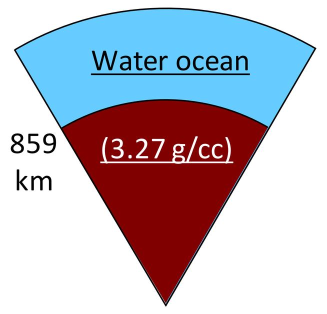
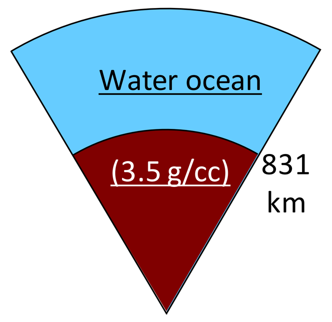
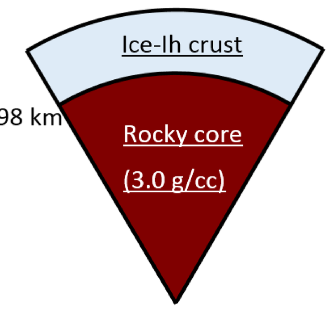
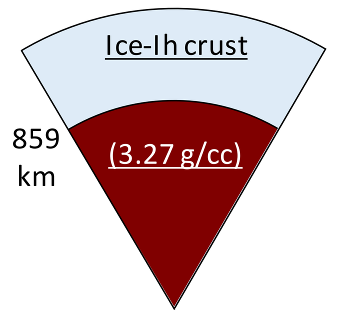
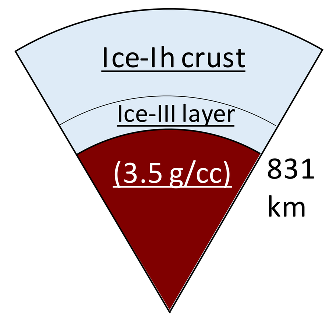


Possible range of Pluto's core radius (solid line) composed of the outer H_2O layer and inner rocky core. HP-ice can be appeared only in the small core case above the core surface when the temperature is sufficiently low.

Large core / Small core



Only ice Ih is appeared. Both ice Ih and ice III can be appeared.

	Large core	Medium core	Small core
Hot Start Entirely molten H_2O layer in initial - Surface: 273.15 K -> 44 K - Ocean: adiabatic T-grad - Core: iso-T of the ocean-core boundary			
Cold Start Entirely frozen H_2O layer in initial - Entirely iso-T of 250 K --> Surface: 44 K			

Numerical frameworks:

Equations: 1-D spherically symmetric model for convective/conductive heat transfer incorporating the radial dependence of viscosity and heat source distributions.
- for solid layers (ice shell, HP-ice layer & rocky core), "Mixing Length Formulation" [6]

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot \mathbf{F} + \rho Q$$
$$\mathbf{F} = F_{cond} + F_{conv}$$
$$F_{cond} = k_c \nabla T$$
$$F_{conv} = k_v (\nabla T - \nabla_{ad} T)$$
$$k_v = \begin{cases} 0 & \frac{\partial T}{\partial r} < \left(\frac{\partial T}{\partial r}\right)_{ad} \\ \frac{\rho C_p \alpha g l^4}{18\nu}\left[\frac{\partial T}{\partial r} - \left(\frac{\partial T}{\partial r}\right)_{ad}\right] & \frac{\partial T}{\partial r} > \left(\frac{\partial T}{\partial r}\right)_{ad} \end{cases}$$

t: time
T: temperature
ρ: density
C_p: specific heat
Q: heat generation
k_c: thermal conductivity
ν: kinetic viscosity
r: radius
α: thermal expansion coef.
l: mixing length
g: gravity

- for the liquid layer (subsurface ocean), "Parameterized Convection Theory".

Rheologies
- liquid water: $\eta_w = 10^{-3}$ Pas
- solid ices: $\eta_{ice} = \eta_{ref} \exp\left[\frac{E_a}{R_g T_m}\left(\frac{T_m}{T} - 1\right)\right]$ $\eta_{ref} = 1 \times 10^{13} \sim 5 \times 10^{17}$ Pas [7]
- rock: $\eta_{rock} = 4.9 \times 10^8 \exp(23.25 T_m/T)$ [8]

Change of the boundary position (M) between solid and liquid (Stefan problem)
- evaluating heat fluxes balance between incoming (F_{in}) and outgoing (F_{out}) at the boundaries. L is the latent heat of ice and M is the position of boundary.

$$\rho L \frac{dM}{dt} = F_{in} - F_{out}$$

Heat sources
- Radiogenic heat only in the rocky core.
- No tidal heating

	CI chondritic (ppb)	Ordinary chondritic
^{238}U	19.9	26.2
^{235}U	5.4	8.2
^{232}Th	38.7	53.8
^{40}K	738	1104

Thermal properties
- solid ices:

$$k_c = \frac{632}{T} + 0.38 - 0.00197T$$
$$\alpha = 3.0 * [(2.5 \times 10^{-7}T) - 1.25 \times 10^{-5}]$$
$$C_p = 7.037T + 185.0$$

- liquid water and rocky material:

Symbol	Meanings	Dimensional value
ρ_{liq}	Density of the liquid H_2O layer	1000 kg/m^3
$C_{p_{liq}}$	Specific heat of the liquid H_2O layer	4.2×10^3 J/K kg
$k_{c_{liq}}$	Thermal conductivity of the liquid H_2O layer	0.566 W/m K
α_{liq}	Thermal expansion coefficient of the liquid H_2O layer	2.1×10^{-4}/K
ρ_c	Density of the rocky core	3000 – 3500 kg/m^3
C_{p_c}	Specific heat of the rocky core	920 J/K kg
k_{c_c}	Thermal conductivity of the rocky core	3.0 W/m K
α_c	Thermal expansion coefficient of the rocky core	2.4×10^{-5}/K

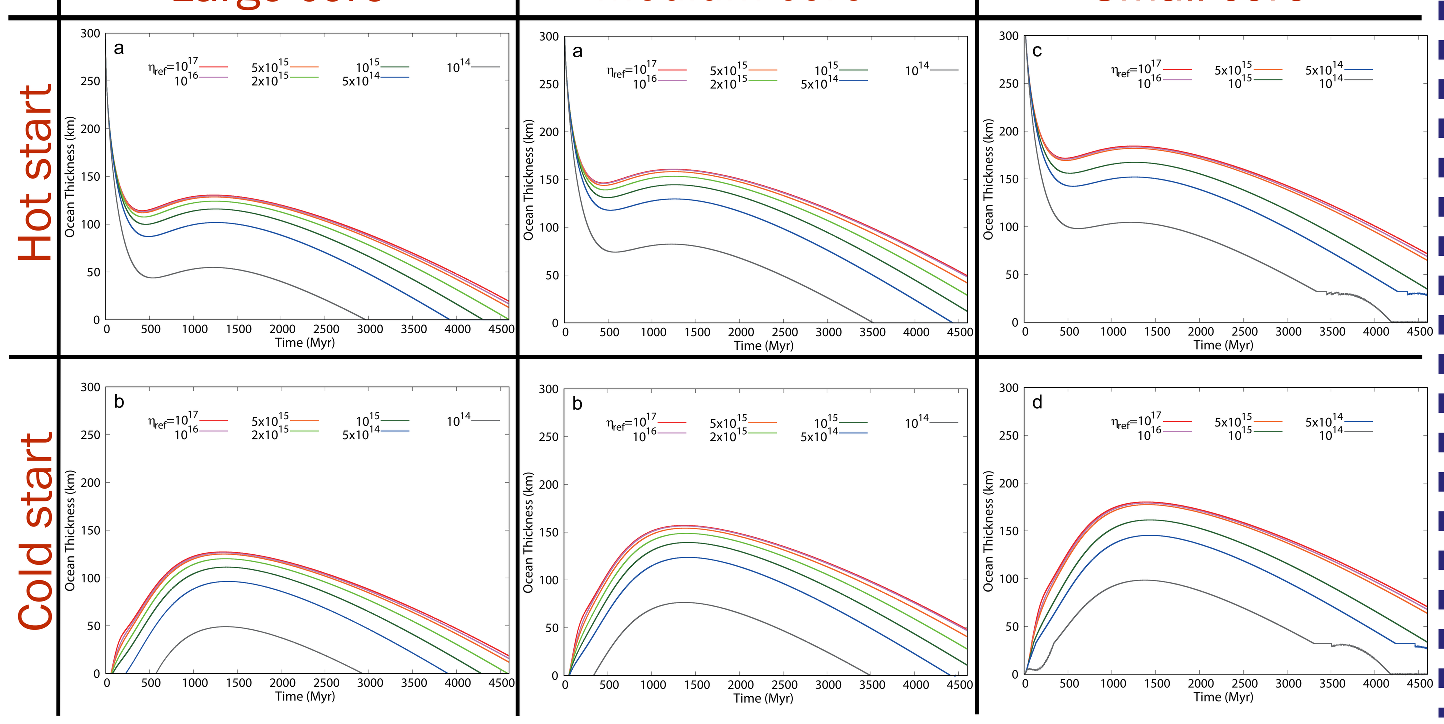
Ocean composition (salinity)
- pure water
- initially 0, 1, 3 wt% NH_3 (salinity changes with freezing the ocean).

Assume that the molten water ascends instantaneously from the core surface to the ocean (or the triple point depth), which corresponds to the extreme case in which the core surface and the ocean are directly connected through a stable upwelling.

Results: Evolution of the Pluto's ocean thickness

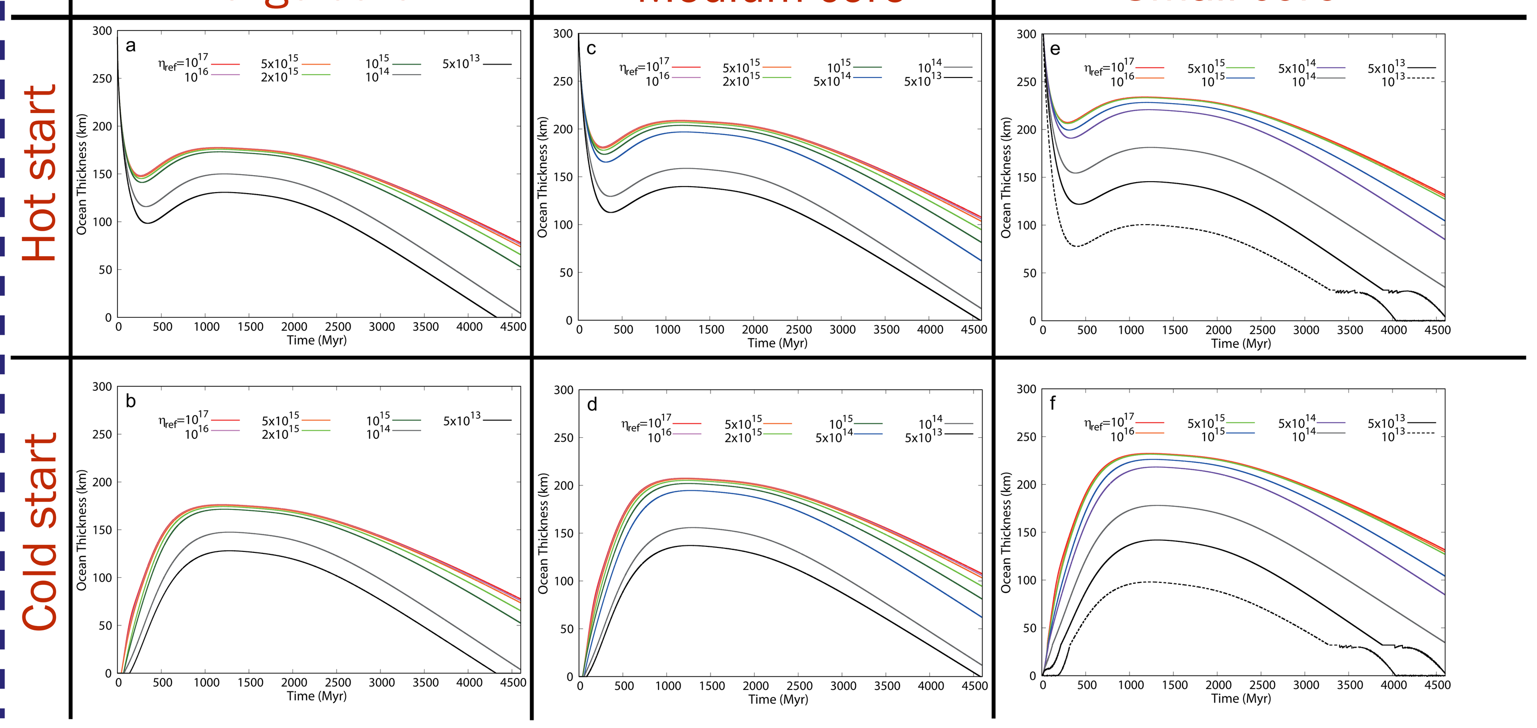
CI chondritic abundance of radioactive isotopes

Large core / Medium core / Small core



Ordinary chondritic abundance of radioactive isotopes

Large core / Medium core / Small core



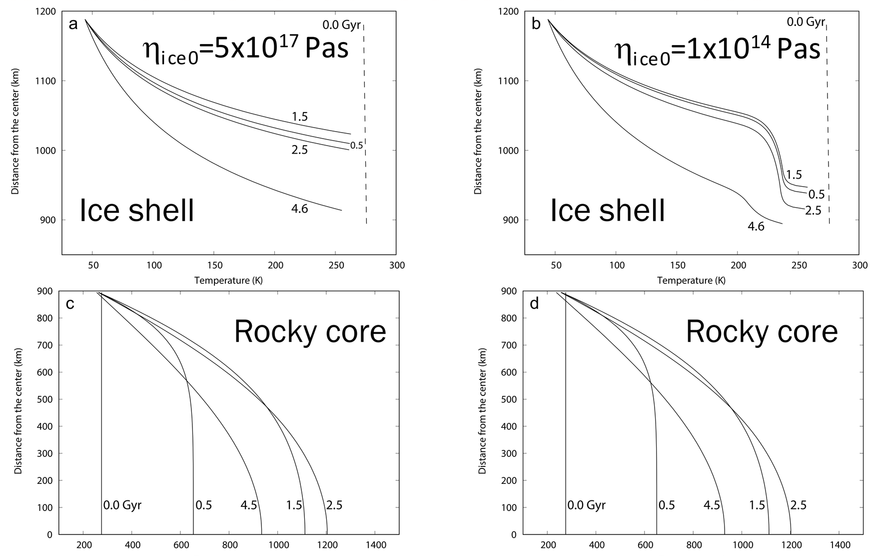
General trend:
- Radiogenic heat from the core is sufficiently high until ~1.5 Gyr, resulting in thinning of the ocean. Thereafter, secular cooling overcomes radiogenic heating, resulting in thickening of the ocean.
- The ice reference viscosity is crucial for an ocean stability because it controls whether convection occurs, and whether an ocean exists at the present. Large ice reference viscosity leads thicker ocean.
- Smaller core leads larger final thickness of the ocean because of the larger amount of radioactive isotopes in the core and the thicker (deeper position of the bottom boundary) water layer.
- Ordinary chondritic radioisotope abundance leads a larger heat flux from the core and a thicker ocean.
- For the small core case, the HP–ice appears above the rocky core but this layer can be molten and a thick ocean in contact with the rocky core may be maintained in a relatively recent period.
- Current Pluto may have an ocean if the ice shell is purely conductive or weakly convective, and its thickness is largely uncertain and can be up to 130 km, depending on the ice reference viscosity.
- Our results also indicate that the initial state affects only little on the evolution scenario. These results strengthen previous conclusions obtained based on thermal evolution studies with limited calculation conditions [5, 6].

Time evolution of temperature profiles

ex.) Large core, hot start and CI chondritic abundance model

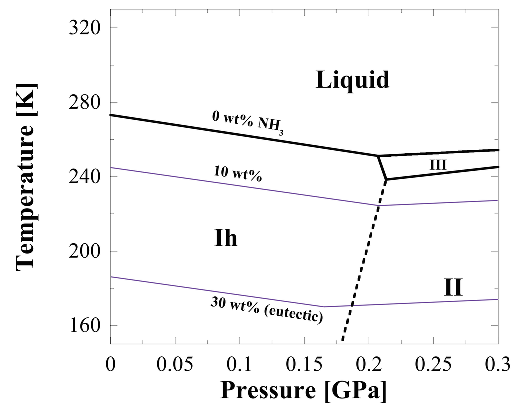
- In case of smaller ice viscosity, the ice shell is convective and effectively transports heat, resulting in a short duration of the ocean.

- Temperature in the rocky core cannot be affected by a thermal state of the ocean and the ice shell because of its large viscosity.

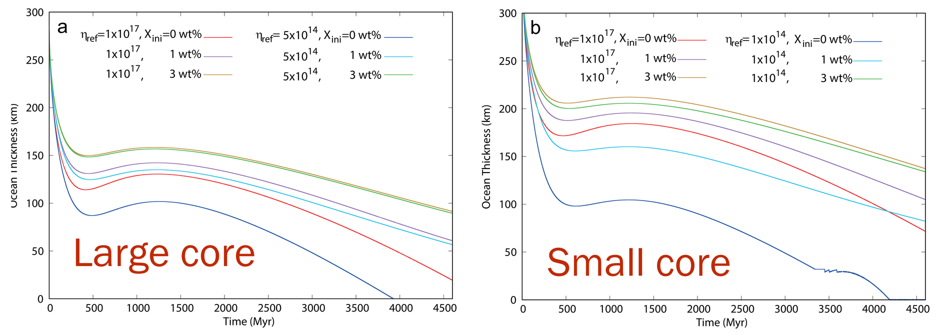


Effect of antifreeze

Presence of NH_3 decreases the melting point of the ocean up to 175 K.



ex.) Large core, hot start & CI chondtiric abundance model



An inclusion of ammonia in the ocean increases the possibility of the current presence of a subsurface ocean even in the case of 1 wt% NH3 at the initial.

Concluding Summary

We investigated Pluto's thermal evolution and stability of the subsurface ocean, and their dependency on the interior structure, the ice viscosity, the radioactive isotope abundances, the initial thermal state, and the dissolved component in the ocean.

The minimum reference viscosities of ice required to maintain the ocean at present:

Radioisotope abundances/ Core size	CI chondritic	Ordinary chondritic
Large core (Rc = 894.5 km)	> $5x10^{15}$ Pas	> $2x10^{14}$ Pas
Medium core (Rc = 859.0 km)	> $1x10^{15}$ Pas	> $1x10^{14}$ Pas
Small core (Rc= 830.5 km)	> $5x10^{14}$ Pas	> $5x10^{13}$ Pas

Initial thermal state does not affect to the current ocean thickness.

Our results find broader conditions to be capable of maintaining the Pluto's ocean at present than previous works depending on the core size. Especially. in case of medium or small core, the ocean can sustain until the present for a typical ice viscosity even without clathrate layer [9].

References
[1] Nimmo+ Icarus 2017, [2] Nimmo+ Nature 2016, [3] Moore+ Nature 2016, [4] Grundy+ Nature 2016, [5] Robuchon and Nimmo Icarus 2011, [6] Kamata JGR 2018 [7] Goldsby and Kohlstedt JGR 2001, [8] Karato+ JGR 1986. [9] Kamata+ Nature Geoscience 2019.