Structure of surface-H_2O layers of ice-covered planets with high-pressure ice

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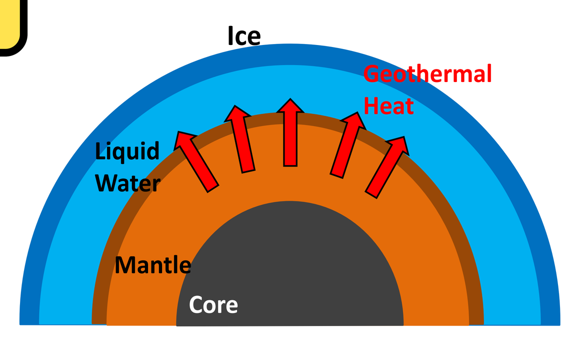
ABSTRACT

Many extrasolar (bound) terrestrial planets and free-floating (unbound) planets have been discovered. The existence of bound and unbound terrestrial planets with liquid water is an important question because it may lead to understanding their habitability. Even in a globally ice-covered planet, geothermal heat flow from the planetary interior is thought to melt the interior ice, creating an internal ocean covered by au ice shell. In this study, we discuss the conditions that terrestrial planets must satisfy for such an internal ocean to exist on the timescale of planetary evolution. In addition, we investigate the structures of surface-H2O layers of ice-covered planets by considering the effects of ice under high pressure (high-pressure ice). The planetary mass and the water abundance on the surface strongly constrain the conditions for an extrasolar terrestrial planet to have an internal ocean with no high-pressure ice under the ocean. Such high-pressure-ice layers underlying the internal ocean are likely to affect the habitability of the planet.

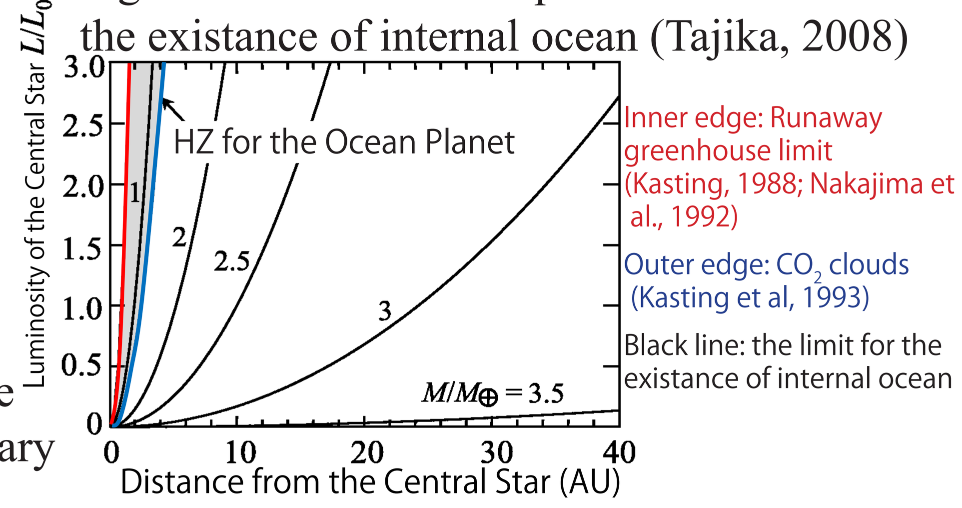
1. INTRODUCTION



Many extrasolar terrestrial (bound) planets and flee-floating (unbound) planets have been discovered.
⇒Whether do terrestrial planets with liquid water exist?
Ice-covered planets ("snowball planets"; Tajika 2008) could have an internal ocean covered by an ice shell because geothermal heat from the planetary interior may melt the interior ice.

In Tajika (2008), he discussed the conditions for an extrasolar terrestrial planet which has an internal ocean for 4.6 billion years.
A planet with a mass > $4M_\oplus$ could have an internal ocean irrespective of planetary orbit and luminosity of the cenral star.

Fig. 1: HZ for the ocean planet and the limit for the existance of internal ocean (Tajika, 2008)



Goal of this study

Tajika (2008)
- Mass-radius relationships without considering compression by gravity
- Fixed thermal conductivity of ice (value at 273 K)
- Radiogenic heat source and H_2O abundance the same as that of the Earth

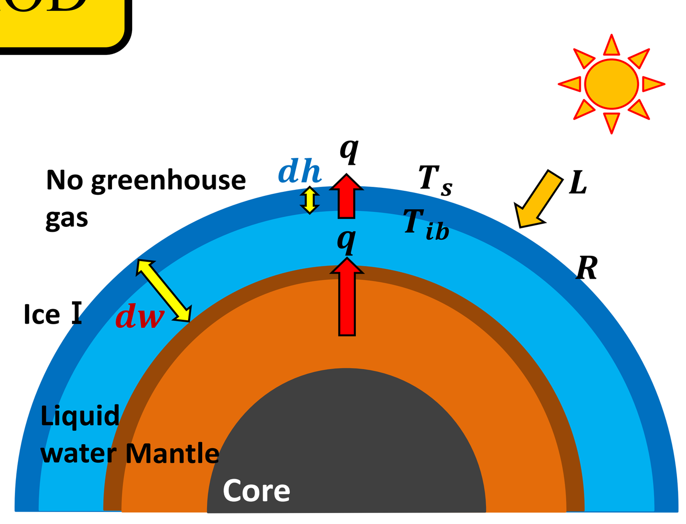
⇩

This Study
- Mass-radius relationships, considering compression by gravity (Valencia et ai., 2006)
- Thermal conductivity, considering tempreture dependence (Klinger, 1980)
- Radiogenic heat source 0.1-10 times that of the Earth
  H_2O abundance 0.1-100 times that of the Earth (0.023 wt.%)

⇒We should consider the effect of "high-pressure ice".

2. METHOD

- $\frac{R}{R_\oplus} = \left(\frac{M}{M_\oplus}\right)^{0.27}$ (Valencia et al, 2006)
- Radiogenic heat source **0.1-10 E_0**
- H2O abundance (Earth: 0.023 wt.%) **0.1-100 M_{sw0}** ⇒dw
- Ice thickness $dh = k_i \frac{T_{ib}-T_s}{q}$
  Thermal conductivity $k_i = \frac{567}{T}$ (Klinger, 1980) ⇒dh
- To have a internal ocean $dw > dh$



- Energy balance on the planetary surface $\frac{(1-A)}{4d^2}\frac{L}{4\pi {D_0}^2} + q = \varepsilon\sigma T s^4$
- Parameterized Convection Model (Tajika & Matsui, 1992)

$$4\pi Rm^2 q + \frac{4}{3}\pi\rho c(Rm^3 - Rc^3)\frac{dT_m}{dt} = \frac{4}{3}\pi E(t)(Rm^3 - Rc^3)$$

Emission to the planetary surface / Thermal evolution of the mantle / Emission from radiogenic heat source

High-pressure Ice

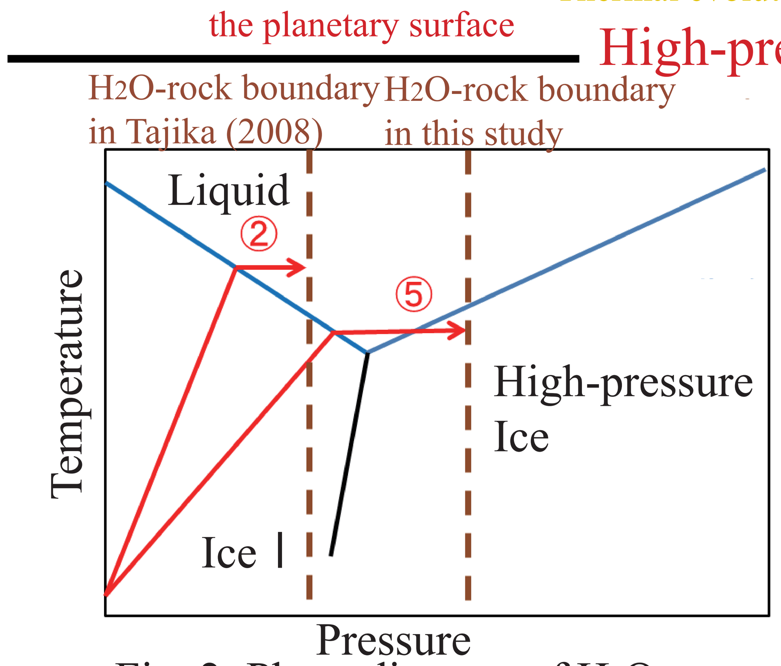


Fig. 2: Phase diagram of H_2O

High- pressure Ice: Ice which goes into the phase transition under high-pressure condition and has larger density than liquid water

We change H2O abundance on the planetary surface.
⇒ H2O thickness increases.

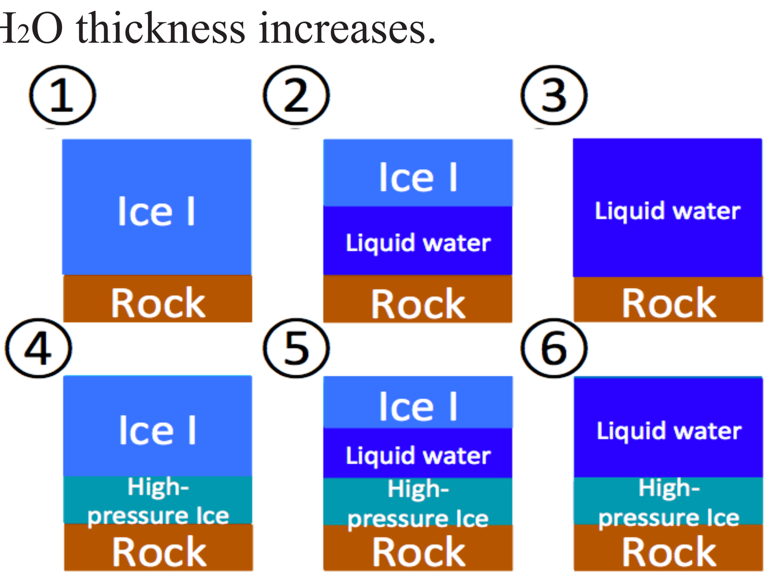


Fig. 3: The surface condition with H_2O

Type 4, 5, and 6 have high-pressure ice layers at the bottom of H_2O layers.
Taking into account the effects of high-pressure ice, we investigate the structure of surface-H_2O layers of ice-covered planets.

3. RESULTS

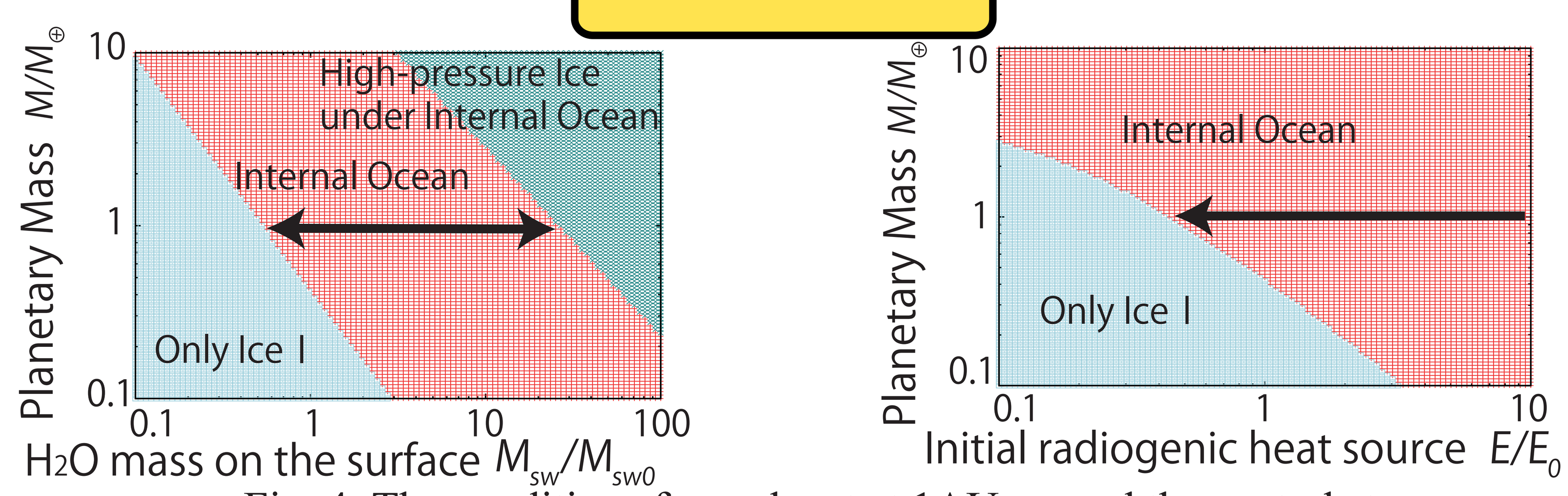


Fig. 4: The conditions for a planet at 1AU around the central star

e.g., A planet which is Earth-mass
0.6-25 M_{sw}/M_{sw0} ⇒Internal Ocean
>25 M_{sw}/M_{sw0} ⇒High-pressure Ice

e.g., A planet which is Earth-mass
>0.4 E/E_0
⇒Internal Ocean

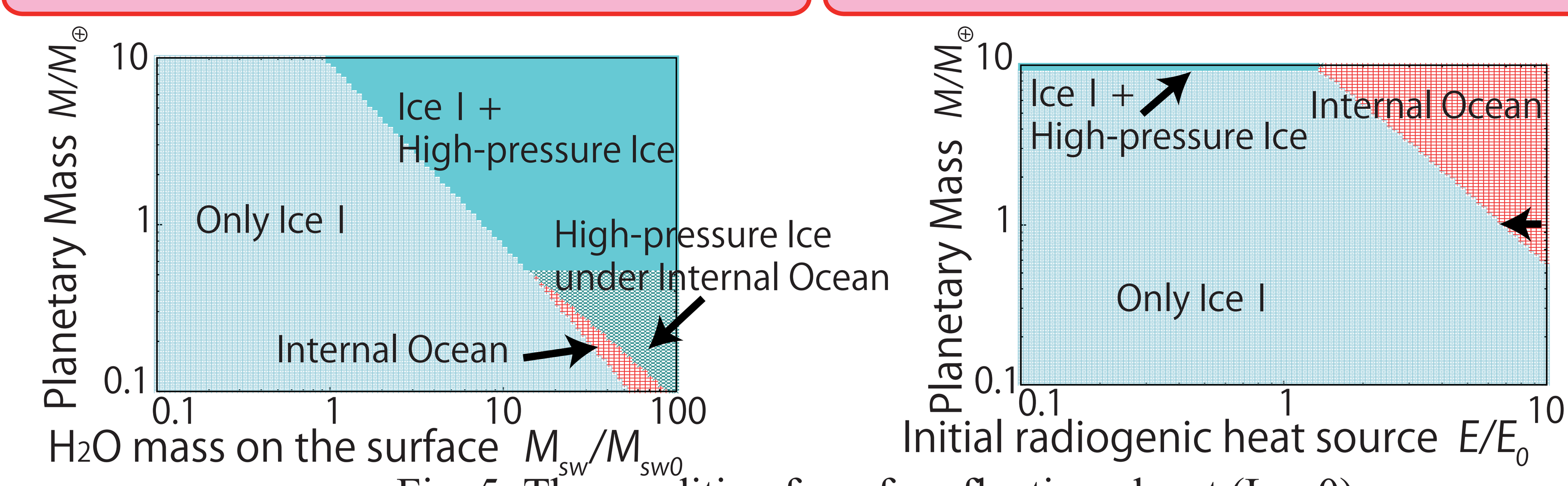


Fig. 5: The condition for a free-floating planet (L = 0)

e.g., A planet which is Earth-mass
⇒It can not have a internal ocean.
The size and the water abundance strongly constrain the condition.

e.g. A planet which is Earth-mass
>7 E/E_0
⇒Internal Ocean

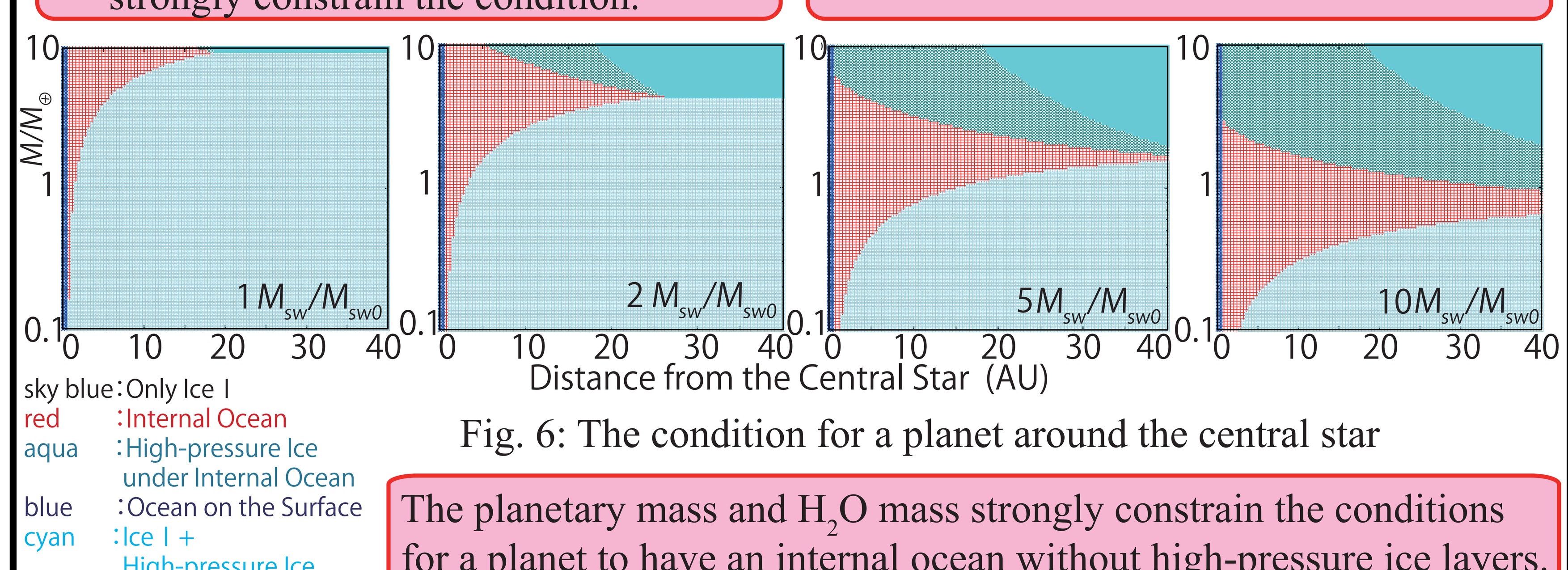


Fig. 6: The condition for a planet around the central star

The planetary mass and H_2O mass strongly constrain the conditions for a planet to have an internal ocean without high-pressure ice layers.

4. DISCUSSION

<Habitability of internal ocean>
For genesis and sustenance of life, we need at least
- liquid water
- nutrient salts

Because nutrient salts are supplied from rocks, it is neccesary that liquid water should be in contact with rock to liberate the salts. A type-5 planets (Fig. 3) is thus not likely to be habitable because the internal ocean does not come in contact with rocks. However, it is possible for a type-2 planet to meet this requirement. Therefore, if we presume that only type-2 planets have an internal ocean that is possibly habitable, the results of this study indicate that only a planet with appropriate planetary mass and H_2O mass can have an internal ocean that is possibly habitable.
In addition, we would need to discuss in the future
- the redox gradient within the internal ocean (e.g., Gaidos et al. 1999)
- the effects of the reverine flux of nutrient salts (Maruyama et al. 2013)

5. CONCLUSION

- We discuss the conditions for bound and unbound terrestrial planets to have an internal ocean.
- By applying the model in Tajika (2008), we also examine the dependencies of radiogenic heat source and H_2O mass on the conditions.
- We investigate the structures of surface-H2O layers of ice-covered planets by considering effects of high-pressure ice.
- The planetary mass and H2O mass on the surface strongly constrain the conditions whether an extrasolar terrestrial planet can have an internal ocean without high-pressure ice under the ocean.
- Such high-pressure-ice layers are likely to affect the habitability of the planet.