CONDITIONS OF SURFACE H2O OF SNOWBALL PLANETS WITH HIGH-PRESSURE ICE S. Ueta[1] and T. Sasaki[1], [1]Earth and Planetary Sciences, Tokyo Institute of Technology (2-12-1 Ookayama, Meguro-ku, Tokyo 152-8551, Japan; ueta@geo.titech.ac.jp, takanori@geo.titech.ac.jp)

Introduction: Since the first extrasolar planet was discovered in 1995 [1], more than 800 exoplanets have been detected as of 2013 March. Although most known exoplanets are gas giants, Earth-like planets have indeed been discovered. Moreover, space telescopes (e.g., Kepler) have now released observational data about many terrestrial planet candidates. Whether terrestrial planets with liquid water exist is an important question to consider because it lays the groundwork for the consideration of habitability.

The orbital range around a star for which liquid water can exist on a planetary surface is called the habitable zone (HZ; e.g., [2]). Planets with plentiful water on the surface but outside the outer edge of the HZ would be globally covered with ice and no liquid water would exist on the surface. These planets are called "snowball planets" [3]. Moreover, an ocean planet could be ice-covered even within the HZ because multiple climate modes are possible, including ice-free, partially ice-covered, and globally ice-covered states (e.g., [3]). Although such planets would be globally ice-covered, liquid water could exist beneath the surface ice shell if sufficient geothermal heat flows up from the planetary interior to melt the interior ice. In this scenario, only a few kilometers of ice would form at the surface of the ocean [4] and life could exist in the liquid water under the surface ice shell (e.g., [5]).

Considering geothermal heat from the planetary interior, Tajika (2008) [3] discusses the theoretical restrictions for ice-covered extrasolar terrestrial planets that, on the timescale of planetary evolution, have an internal ocean. In this paper, we extend the analysis of [3] and vary the parameter values such as the abundance of radiogenic heat sources and the H_2O abundance on the surface. We also check whether ice appears under H_2O layers under high-pressure conditions (high-pressure ice). Therefore, in this work, we consider the effect of high-pressure ice under an internal ocean and discuss its implications for habitability (see Discussion). Finally, we investigate the structure of surface H_2O layers of ice-covered planets by taking into account the effects of high-pressure ice.

Method: *Numerical model.* The planetary surfaces are assumed to consist of frozen H_2O and to have no continental crust. We define the planetary radius as $R=dw+l$, where dw is the H_2O thickness and l is the mantle-core radius. The mass of H_2O on the planetary surface is given by

$$M_{sw} = (4/3)\pi\rho_w[(dw + l)^3 - l^3], \quad (1)$$

where ρ_w is the density of H_2O. We vary M_{sw} from 0.1 M_{sw0} to 100 M_{sw0}, where M_{sw0} = 0.00023M and M is the planetary mass, with the coefficient being the H_2O abundance of Earth (0.023% by weight). Assuming that a heat flux q is transferred from the planetary interior through the surface ice shell by thermal conduction, the ice thickness dh can be calculated as

$$dh = k_i(T_{ib} - T_s)/ q, \quad (2)$$

where k_i is the thermal conductivity of ice, T_{ib} is the temperature at the bottom of the ice, and T_s is the temperature at the surface. From these models, we can obtain the H_2O thickness dw and the ice thickness dh. The condition for terrestrial planets having an internal ocean is

$$dw > dh. \quad (3)$$

To estimate the geothermal heat flux q through planetary evolution, we investigate the thermal evolution of terrestrial planets using a parameterized convection model (e.g., [6]). We assume E, which is the initial heat generation per unit time and volume, to be $0.1E_0$–$10E_0$, where the constant E_0 is the initial heat generation estimated from the present heat flux of the Earth.

High-pressure ice. Ice undergoes a phase transition at high pressure. Unlike ice Ih, the other phases are more dense than liquid H_2O. We call the denser ice "high-pressure ice." Because Tajika (2008) [3] assumes that the amount of H_2O on the planetary surface is the same as that on the Earth's surface M_{sw0} (= 0.00023M), the only possible conditions on the planetary surface are those labeled 1, 2, and 3 in Figure 1. However, because we consider herein that H_2O mass may range from 0.1 M_{sw0} to 100 M_{sw0}, the H_2O–rock boundary could move to higher pressure, so we should account for the effect of high-pressure ice (Figure 1(a)). Therefore, types 4, 5, and 6 of Figure 1(b) are added as possible surface conditions. Type 2 and type 5 planets both have an internal ocean, but high-pressure ice exists in type 5 planets between the internal ocean and the underlying rock.

Results: Figures 2(a) and (b) show the surface conditions for planets with masses from 0.1 $M_\oplus$ to 10 $M_\oplus$ 4.6 billion yr after planetary formation, with varying H_2O masses on their surfaces or initial radiogenic heat sources. All of the planets are located 1 AU from thier central star. We assumed E/E_0 = 1 for Figure 2(a) and M_{sw}/M_{sw0} = 1 for Figure 2(b). Because larger planets have larger geothermal heat fluxes and thicker H_2O layers, these objects could have an internal ocean with a smaller H_2O mass on the planetary surface (Figure 2(a)) and a weaker initial radiogenic heat source (Figure 2(b)). However, larger planets also have larger gravitational accelerations. Thus, on those planets, high-pressure ice tends to appear under the internal ocean with a smaller H_2O mass on the surface (Figure 2(a)). For example, if a planet of mass $1M_\oplus$ has an H_2O mass of 0.6 M_{sw0}–25 M_{sw0}, it could have an internal ocean. However, if a planet has an H_2O mass > $25M_{sw0}$, high-pressure ice should exist under the ocean (Figure 2(a)). Note, however, that an internal ocean can exist on a planet having a mass of $1M_\oplus$ if the initial radiogenic heat source exceeds $0.4E_0$ (Figure 2(b)).

Figures 3(a) and (b) show the surface conditions for free- floating planets (L = 0) with masses from 0.1 $M_\oplus$ to 10 $M_\oplus$ 4.6 billion yr after planetary formation. The incident flux from the central star affects the surface temperature, thereby affecting the condition on the surface. Therefore, the conditions, and in particular those shown in Figure 3(a), are different from those shown in Figures 3(a) and (b). The results of Figure 3(a) show that, regardless of the amount of H_2O a $1M_\oplus$ planet has, an internal ocean cannot exist under the ice shell. An internal ocean could exist on free-floating planets under certain conditions, but the planetary size and water abundance strongly constrain these conditions (see Figure 3(a)). For instance, if a free-floating planet has an initial radiogenic heat source greater than $7E_0$, it can have an internal ocean (Figure 3(b)).

Discussion: For genesis and sustenance of life, we need at least (1) liquid water and (2) nutrient salts because these substances are required to synthesize the body of life [7]. Because nutrient salts are supplied from rocks, it is necessary that liquid water be in contact with rock to liberate the salts. A type 5 planet (Figure 1(b)) is thus not likely to be habitable because the internal ocean does not come in contract with rocks. However, it is possible for a type 2 planet to meet this requirement. We presume that only type 2 planets have an internal ocean that is possibly habitable. Therefore, the results of this study indicate that only a planet with the appropriate planetary mass and H_2O mass can have an internal ocean that is possibly habitable.

Conclusions: Herein, we discuss the conditions that must be satisfied for ice-covered bound and unbound terrestrial planets to have an internal ocean on the timescale of planetary evolution. Geothermal heat flow from the planetary interior is considered as the heat source at the origin of the internal ocean. By applying and improving the model of Tajika (2008), we also examine how the amount of radiogenic heat and H2O mass affect these conditions. Moreover, we investigate the structures of surface H2O layers of snowball planets by considering the effects of high-pressure ice. The results indicate that planetary mass and surface H2O mass strongly constrain the conditions under which an extrasolar terrestrial planet might have an internal ocean without high-pressure ice existing under the internal ocean.

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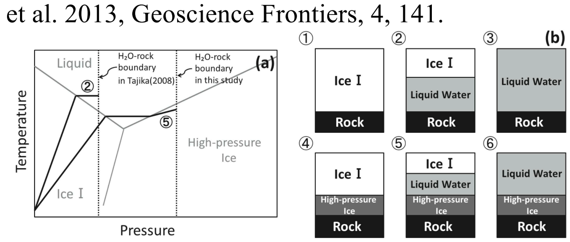

Figure 1. (a) Schematic phase diagram of H_2O (gray lines), temperature gradient (black lines), and H_2O–rock boundaries (dashed lines). (b) Types of planets that have H_2O on their surfaces.

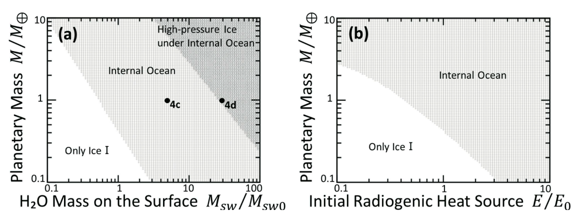

Figure 2. Surface conditions for a planet at 1 AU around a central star ($L = L_0$; the present luminosity of our Sun). (a) The x axis is the surface H_2O mass and the y axis is planetary mass normalized by the Earth's mass, assuming E/E_0 = 1. (b) The x axis is initial radiogenic heat, and the y axis is the planetary mass normalized by the Earth's mass, assuming M_{sw}/M_{sw0} = 1.

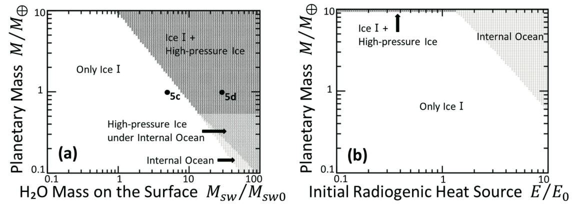

Figure 3. Same as Figure 2, but for a free-floating planet (L = 0).