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SNOWBALL PLANETS AS A POSSIBLE TYPE OF WATER-RICH TERRESTRIAL PLANET IN EXTRASOLAR PLANETARY SYSTEMS

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ABSTRACT

Terrestrial planets with abundant water have multiple climate modes, including an ice-free, a partially ice-covered, and a globally ice-covered state. Recent geological studies have revealed that the Earth experienced global glaciations in its history ("snowball Earth" hypothesis). In the snowball glaciations, liquid water is thought to have existed under the ice shell because of geothermal heat flow from the Earth's interior. Here, by analogy with the snowball glaciations, I discuss the conditions for an extrasolar terrestrial planet which is covered with ice but has an internal ocean for the timescale of planetary evolution owing to geothermal heat flow from the planetary interior. I show that liquid water can exist if the planetary mass and the water abundance are comparable to the Earth, although a planet with a mass $<0.4\ M_\oplus$ ($M_\oplus$ is the Earth's mass) would not be able to maintain the internal ocean. Liquid water would be absolutely stable for a planet with a mass $\gtrsim 4\ M_\oplus$ (i.e., super-Earth) either on its surface or beneath the ice, irrespective of planetary orbit and luminosity of the central star. Searches for terrestrial planets in extrasolar planetary systems should consider such a "snowball planet," which is a possible type of water-rich terrestrial planet other than an Earth-like "ocean planet."

Subject headings: astrobiology — planetary systems — planets and satellites: general

1. INTRODUCTION

The presence of liquid water is essential for life, so a terrestrial planet covered with a large amount of liquid water (hereafter called an "ocean planet"), such as the Earth, has been considered habitable. The region around a star which satisfies the condition for the presence of liquid water is termed the habitable zone (HZ) (Hart 1979; Kasting et al. 1993). An ocean planet is, however, known to have multiple climate modes, including an ice-free state, a partially ice-covered state, and a globally ice-covered state (Budyko 1969; Sellers 1969). This means that the ocean planet could be globally ice-covered, even if it is within the HZ.

Because liquid water cannot exist beyond the runaway greenhouse limit (Kasting 1988; Nakajima et al. 1992), the inner edge of the HZ is 0.84 AU for the present luminosity of our Sun (L_0) (Fig. 1).

On the other hand, the outer edge of the HZ is somewhat controversial. If there is no greenhouse gas in the planetary atmosphere, it can be defined here as an orbit at which an effective temperature (T_e) is 273 K. Considering the energy balance on the planetary surface, $(1 - A)S/4d^2 = \varepsilon\sigma T_e^4$, where A is the planetary albedo, S is the incident energy flux at 1 AU (i.e., $S = L/4\pi D_0^2$, where $D_0 = 1.5 \times 10^8$ m), d is the distance from the central star in AU, ε is the emissivity, and σ is the Stefan-Boltzmann constant, we obtain $d = 0.87$ AU when we assume $T_e = 273$ K, $A = 0.3$, and $\varepsilon = 1$ for the present luminosity of our Sun. For a planet orbiting at $d <$ 0.87 AU, there is only one solution (not multiple solutions) for the energy balance—an ice-free solution. This should be the most conservative estimate, resulting in the HZ being very narrow (0.84–0.87 AU; Fig. 1).

It is, however, quite natural that the ocean planet could have an atmosphere which contains some greenhouse gases, such as CO_2 and/or CH_4; hence the outer edge could extend outward ($\varepsilon < 1$; Fig. 1). In fact, the Earth is orbiting outside 0.87 AU but habitable because of the greenhouse effect of the atmosphere. In this case, condensation of CO_2 to form CO_2 clouds may limit the outer edge (1.37 AU) (Kasting et al. 1993), although the CO_2 clouds could scatter infrared emitted from the planetary surface and result in warming (Forget & Pierrehumbert 1997). The outer edge might therefore further extend outward to at least 1.67 AU (the maximum greenhouse limit of Kasting et al. 1993), or perhaps ~2.4 AU (Mischna et al. 2000). This is the HZ considered generally for the ocean planet.

Here, if the planetary orbit is within the HZ for the ocean planet but outside the HZ in the narrow sense (0.87 AU < d $\lesssim$ 2.4 AU for L_0), and if the warm climate is maintained by greenhouse effect of the atmosphere, there is a paradox: CO_2, which is the most common greenhouse gas in the atmosphere of the terrestrial planets, is consumed through chemical weathering followed by carbonate precipitation in the ocean (Walker et al. 1981). In other words, CO_2 is lost if there is liquid water, resulting in a globally ice-covered state. Although a negative feedback mechanism due to temperature dependency of silicate weathering rate could have stabilized the climate of the Earth (Walker et al. 1981), CO_2 should be supplied continuously to the surface via volcanism, hence plate tectonics would be necessary for maintaining the warm climate (Tajika 2007).

The Earth may, however, have been globally glaciated at least three times in its history (the snowball Earth hypothesis) (Kirschvink 1992; Hoffman et al. 1998; Kirschvink et al. 2000; Hoffman & Schrag 2002). This might suggest that even when plate tectonics works, the volcanic CO_2 supply may not always be continuous or large enough to keep the climate above a critical level (Tajika 2003, 2004, 2007). This is, again, a result of the Earth orbiting outside the HZ in the narrow sense.

In the snowball glaciations, geothermal heat flow from the Earth's interior would have inhibited the deep ocean from complete freezing. As a result, only the surface ~1000 m of the ocean would have frozen (Hoffman & Schrag 2002). Liquid water existed under the ice shell, and life could have survived through the snowball glaciations (Hoffman et al. 1998; Hoffman & Schrag 2002; Gaidos et al. 1999).

In the extrasolar planetary systems, there would be terrestrial planets on which conditions are quite different from the Earth.

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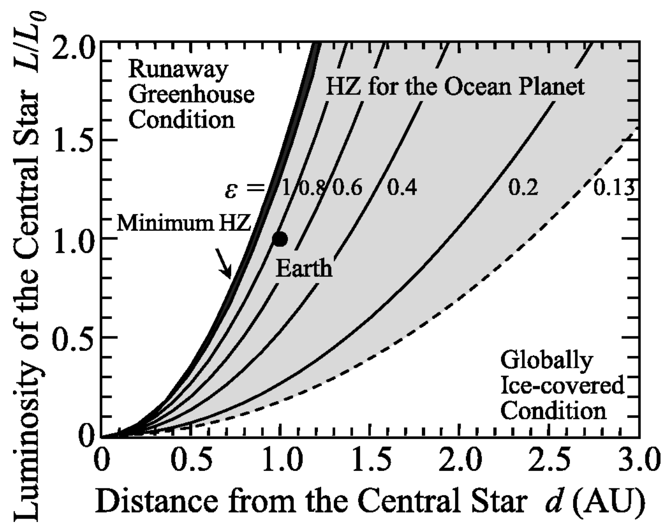

FIG. 1.—Habitable zone (HZ) around main-sequence stars. The region with light gray shading represents the HZ for the Earth-like ocean planet (Kasting et al. 1993; Mischna et al. 2000). The region with dark gray shading (denoted by "minimum HZ") represents the HZ in the narrow sense (0.84 AU $\leq d \leq$ 0.87 for $L/L_0 = 1$) which is defined here as the region between the runaway greenhouse limit (Kasting 1988; Nakajima et al. 1992) and the orbit at which the effective temperature is 273 K for the planet with no greenhouse gas in the atmosphere ($\varepsilon = 1$) and $A = 0.3$. Solid curves represent the orbits at which the surface temperature is 273 K for the planet with some greenhouse gases in the atmosphere ($\varepsilon < 1$) and $A = 0.3$. Filled circle represents the present condition for the Earth.

For example, because hot-spot-type volcanism due to a rise of mantle plumes would be the most common type of volcanism on the terrestrial planet (as seen on Venus, Mars, and Earth), there may be terrestrial planets without volcanism due to plate tectonics. On such planets, the CO_2 supply could be intermittent and insufficient for maintaining a warm climate. Also, there may be terrestrial planets orbiting outside the HZ for the ocean planet. These planets would be inevitably globally ice covered. On the analogy of the snowball glaciations, however, there is a possibility that liquid water exists beneath the surface ice shell even when the planetary surface is covered with ice.

In this study, theoretical constraints on terrestrial planets with liquid water underneath the surface ice shell are investigated in order to understand characteristic features of a possible type of terrestrial planet expected to be observed in extrasolar planetary systems in the future.

2. NUMERICAL RESULTS

In order to estimate variations of geothermal heat flow q from the interior through planetary evolution, thermal evolution of the terrestrial planet with the same abundance of radiogenic heat sources (^{238}U, ^{235}U, ^{232}Th, ^{40}K) as those in the Earth's mantle is investigated by using a parameterized convection model (Tajika & Matsui 1992) (Fig. 2*a*).

The heat flow for a planet with a mass of 0.1–10 $M_\oplus$ at 4.6 billion years since the planetary formation is estimated to be in the range of 40–200 mW m^{-2} (Fig. 2*a*), comparable to that of the Earth at present (87 mW m^{-2}) (Stein 1995). These values can be converted to an equilibrium ice thickness (ΔH), assuming that the same amount of heat flow from the planetary interior is transferred through the surface ice shell by thermal conduction ($\Delta H = k\Delta T/q$, where k is the thermal conductivity of ice and ΔT is the temperature difference between the surface and bottom of the ice).

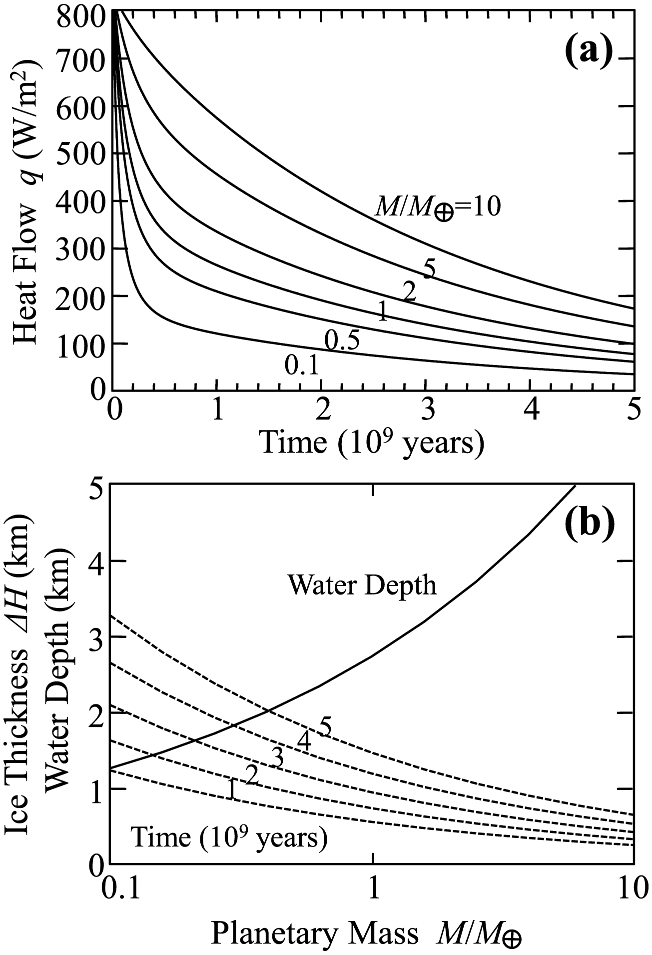

FIG. 2.—Heat flow and ice thickness. (*a*) Temporal variations of heat flow for the terrestrial planets with masses of 0.1–10 $M_\oplus$ obtained from calculations of thermal evolution of the planets with a parameterized convection model. (*b*) Temporal variations of ice thickness for the planets around the Sun with masses of 0.1–10 $M_\oplus$ at $d = 1$ and $A = 0.62$. It is assumed that there is no greenhouse gas in the planetary atmosphere ($\varepsilon = 1$) for 5 billion years without any supply of CO_2 to the atmosphere in order to obtain an upper estimate of the ice thickness. Here, the luminosity increase due to the evolution of the Sun as a main-sequence star (Gough 1981) is considered. The surface temperature of the planet therefore changes with time. The water depth is estimated by assuming a water abundance the same as that of the Earth (0.023 wt.%) and no continental crust on the planetary surface (hence it provides a lower estimate of the water depth).

We can see that if a planet at 1 AU around our Sun with the same water abundance as that of the Earth (0.023 wt.%) is globally glaciated, the heat flow on the planet with a mass >0.4 $M_\oplus$ would be large enough to sustain liquid water for the timescale of planetary evolution (Fig. 2*b*). This means that liquid water is generally stable on these planets even when the surface is covered with ice. Such a planet may be termed a "snowball planet." A Mars-sized planet (0.1 $M_\oplus$) is, however, too small to keep the heat flow high enough to maintain liquid water except during its earliest history (Fig. 2*b*).

The incident flux from the central star affects the surface temperature, hence the ice thickness. The effect is estimated for different values of luminosity of the central star and the semimajor axis of the planetary orbit (Figs. 3 and 4). The results suggest that the ice thickness increases with distance from the central star because of a decrease in the incident flux. The internal ocean of the snowball Earth, for example, would survive as far as $d \sim 4$ AU from the Sun (for a water depth of

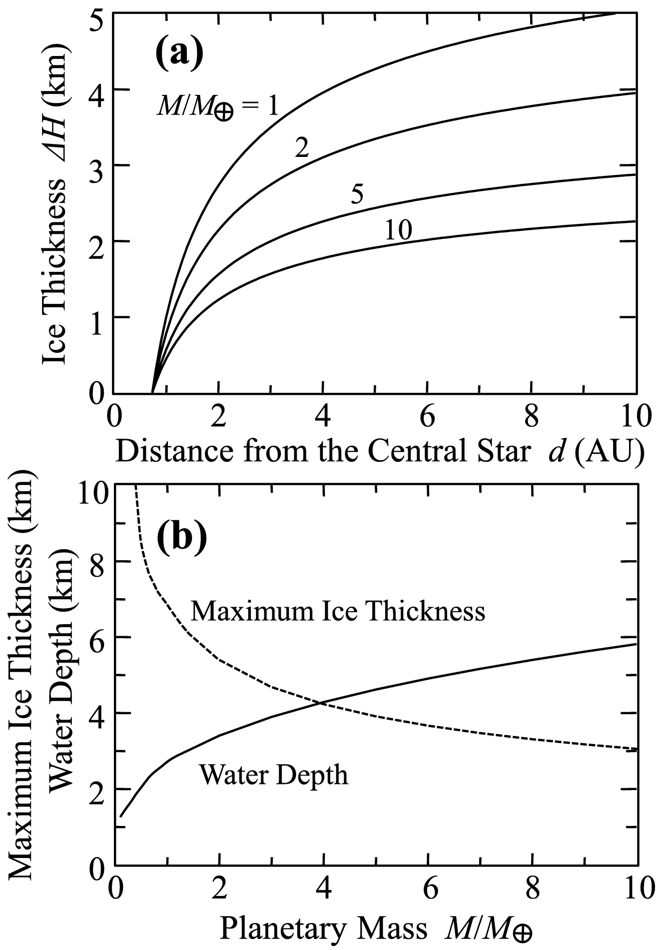

FIG. 3.—Limit of the planetary mass above which liquid water exists. (*a*) Ice thickness as a function of planetary mass and distance from the central star with the present luminosity of our Sun. Because of higher heat flow, ice thickness is thinner for larger planets. (*b*) The water depth and the maximum ice thickness as a function of planetary mass. The maximum ice thickness is defined here as the ice thickness estimated by assuming the surface temperature to be 0 K (hence assuming the maximum temperature gradient in the ice). It is apparent that the internal ocean cannot freeze completely if the planetary mass is $\gtrsim 4\ M_\oplus$, irrespective of the orbit and the luminosity of the central star.

~4000 m; Fig. 3*a*). Because larger planets have higher heat flow and larger amounts of water (Figs. 2*a* and 2*b*), the outer limit is expected to be very distant (Fig. 3*a*).

In fact, because the ice thickness decreases with the planetary mass (Fig. 3*a*) while the water depth increases, the internal ocean cannot freeze completely for planets with masses $\gtrsim 4\ M_\oplus$ (Fig. 3*b*). This is because the heat flow is too large to be transported by heat conduction through the ice shell with the whole ocean thickness, even if the surface temperature is as low as 0 K. It is, therefore, almost certain that liquid water exists on the super-Earth (Valencia et al. 2007) either on its surface (as an ocean planet) or beneath the ice shell (as a snowball planet), except for those orbiting inside the runaway greenhouse limit. As shown in Figure 4, the internal ocean of the snowball planet with a mass $>3.5\ M_\oplus$ is maintained even at the orbit of the Edgeworth-Kuiper belt objects (40 AU). It is, therefore, suggested that if the subsurface ocean on the snowball planet could be habitable for life, life might well exist far outside the HZ for the traditional ocean planet.

3. DISCUSSION

On Earth, many extant clades of eukaryotic algae have survived through the Neoproterozoic snowball glaciations. This might imply that there was liquid water on the ice surface or within the photic zone (the upper ~100 m of the ocean). Such a condition may have resulted because (1) there were many shallow hot springs around volcanic islands (Hoffman et al. 1998; Hoffman & Schrag 2002), (2) there were regions with very thin ice (< 30 m) through which sunlight penetrated and life could have photosynthesized beneath the sea ice (McKay 2000; Warren et al. 2002; Goodman & Pierrehumbert 2003; Pollard & Kasting 2005), (3) the equatorial oceans did not freeze while the equatorial continents were covered with ice (Hyde et al. 2000), and/or (4) the ice surface could have melted seasonally. These arguments might provide insight into habitability of the snowball planet.

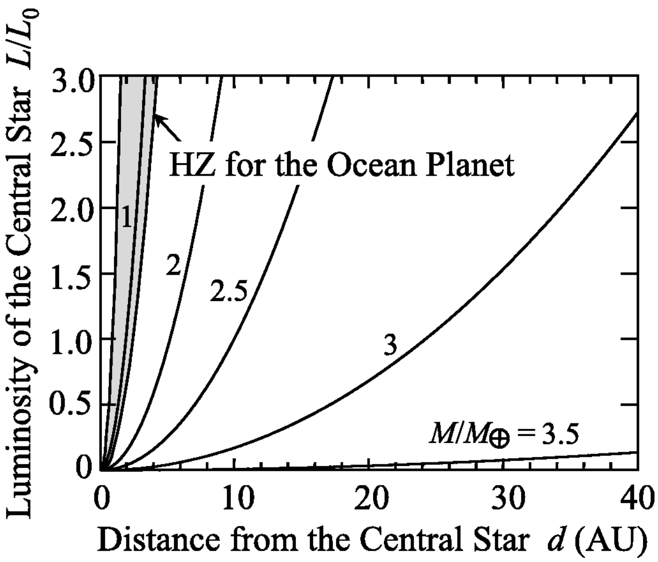

FIG. 4.—Limit of the distance from the central star for the existence of subsurface liquid water. As the planetary mass increases, the ice thickness decreases while the water depth increases. Therefore, liquid water under the ice shell may not freeze completely for a planet with a mass of 3.5 $M_\oplus$ even when the distance from the central star is as far as 40 AU. The region with light gray shading represents the HZ for an Earth-like ocean planet (see Fig. 1).

On the snowball planet, accumulation of CO_2 in the atmosphere through volcanic activities (Kirschvink 1992) would eventually melt the ice shell completely. If the volcanic flux of CO_2 is too low to sustain a warm climate, however, the planet would soon freeze again. Global-scale melting and freezing may repeat on the snowball planet.

The timescale for the snowball-Earth events has been estimated from the timescale for CO_2 to accumulate in the atmosphere due to volcanic CO_2 supply to a level required for melting of ice. This timescale is estimated to be on the order of 10^6 yr for the Neoproterozoic to 10^7 yr for the Paleoproterozoic snowball-Earth events (Caldeira & Kasting 1992; Hoffman et al. 1998; Kirschvink et al. 2000). Therefore, the total duration of the snowball glaciations would be a few percent of the Earth's history. Sleep and Zahnle suggested that the early Earth might have been globally glaciated owing to chemical weathering of ultramafic volcanics and impact ejecta for the first few hundred million years (Sleep & Zahnle 2001; Zahnle 2006). Considering such a possibility, the total duration of the snowball glaciations may be at most 10% of the Earth's history. It would be difficult for a distant observer to observe the globally ice-covered Earth.

There could be, however, extrasolar terrestrial planets more susceptible to being globally ice covered than the Earth. For example, a water-rich terrestrial planet orbiting outside the HZ for ocean planets would be persistently ice covered until the central star evolves to be bright enough. Also, on the planets without plate tectonics, the CO_2 supply via hot-spot-type volcanism would be intermittent and insufficient for maintaining a warm climate. It would take a much longer timescale to escape from the snowball glaciations, and the planet would soon fall into snowball glaciations again. For such planets, the globally ice-covered would be the ordinary state, and there may be a chance to observe them.

The abundance of water on terrestrial planets has been a matter of debate. Planetesimals with chondoritic composition or icy planetesimals formed at the inner region of optically thick protoplanetary disk may supply a large quantity of water to terrestrial planets during the accretion stage (Matsui & Abe 1986; Machida & Abe 2006; Raymond et al. 2004), while comets may also deliver water after planetary formation (Chyba 1987). Another possibility is that hydrogen captured by accreting protoplanets from protoplanetary nebulae can be oxidized to produce abundant water (Ikoma & Genda 2006). Recent discovery of water vapor within 1 AU of the protoplanetary disk around the young star MWC 480 may suggest migrating icy bodies and evaporated water vapor as possible H_2O sources for terrestrial planets (Eisner 2007). Considering all these possibilities, terrestrial planets can be expected to have some water.

In our solar system, however, only the Earth is an ocean planet. Both Venus and Mars are neither ocean planets nor snowball planets. Because Venus is well within the runaway greenhouse limit, water has been photodissociated followed by the escape of hydrogen to space (Kasting 1988). For Mars, the mass may be too small to maintain liquid water, if the ocean once had existed (Fig. 2*b*). On the other hand, Europa and Callisto are thought to have internal oceans due to tidal heating by enormous gravity of Jupiter. These icy satellites may be classified into a kind of the snowball planet, although such small bodies may not be habitable due to a lack of redox gradient within the internal ocean (Gaidos et al. 1999).

The snowball planet might even be a common type of water-rich terrestrial planet, because (1) the globally ice-covered state is one of the stable solutions of the energy balance for the ocean planet, (2) the most general type of volcanic activity on the terrestrial planet is hot-spot-type volcanism which occurs intermittently and is insufficient for maintaining a warm climate, and (3) the condition for the presence of liquid water under the ice shell depends weakly on volcanic activities and incident solar flux, but depends strongly on internal heat flow which remains large enough over the planetary evolution.

The search for terrestrial planets in the extrasolar planetary system will focus on the search for Earth-like ocean planets by measuring the spectrum of the atmosphere and trying to detect H_2O, O_2, and O_3, which imply the presence of liquid water and/or photosynthetic organisms. We should, however, also consider another type of water-rich terrestrial planet which may not have detectable signals of these molecules, but have low brightness temperatures and very high planetary albedo with a mass comparable to the Earth.

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