Formation, Detection, and Characterization of Extrasolar Habitable Planets
Proceedings IAU Symposium No. 293, 2012
N. Haghighipour, ed.

doi:10.1017/S1743921313013082

Re-Evaluation of the Inner Edge of Habitable Zone

Takanori Kodama[1], **Hidenori Genda**[2], **Yutaka Abe**[1] **and Kevin Zahnle**[3]

[1]Department of Earth and Planetary Science, The University of Tokyo,
7-3-1, Hongo, Bunkyo-ku, Tokyo, Japan
email: koda@eps.s.u-tokyo.ac.jp

[2]Earth-Life Science Institute, Tokyo institute of Technology,
2-12-lE-1, Ookayama, Meguro-ku, Tokyo, Japan
[3]NASA Ames Research Center,
Moffett Field, California, USA

Abstract. Existence of liquid water on the planetary surface is thought to be an important condition for the origin and evolution of life. Planets with oceans (or lakes) are classified in two types: Earth-like 'aqua planets' and less water 'land planets'. The latter shows stronger resistance than the former to the runaway greenhouse caused by the increase of stellar luminosity. We examined the possibility of evolution from an aqua planet to a land planet by water loss. We showed that an aqua planet with less than about 0.1 present Earth's ocean mass can evolve to a land planet without having experience of the runaway greenhouse, and maintains liquid water on its surface for about 2Gyrs longer than planets with larger amount of water. Our results mean that the initial amount of water is important for their evolution paths and habitability.

Keywords. Habitability; Habitable Zone; stellar insolation

1. Introduction

Many planets with several times of Earth mass have been detected and their habitability is also discussed actively. Planets with liquid water on their surface are classified in two modes: the aqua planet mode and the land planet mode. On previous studies, planets with ocean globally have been assumed and their climate has been discussed. The increase of the stellar luminosity causes warming of the planets and enhancement of water vapor in their atmosphere and drives the loss of water into the space and the complete evaporation of water through the runaway greenhouse. For evolution path of such planets, both of them are thought to terminate the habitable world. The habitable zone (HZ) has been defined as the region around the central star where liquid water is stable on the planetary surface. The inner edge of the HZ is determined by such a rapid water loss (Kasting *et al.* 1993; Kopparapu *et al.* 2013). On land planet, the distribution of ground water is controlled by the atmospheric circulation, thus, water accumulates in the cool region of the planet (Abe *et al.* 2011). On the other hands, planets with ocean globally are called "aqua planet". Because of the difference in the water distribution, a land planet maintains liquid water at much larger isolation than an aqua planet.

However, if a planet on the aqua planet mode evolves to the land planet mode by a rapid water loss before the onset of the runaway greenhouse, it can maintain liquid water on its surface for another 1 Gyr or so, because the land planet mode is strongly resistance to both the water loss and the runaway greenhouse.

Whether an aqua planet follows such an evolution path or not is controlled by the race, which is depended on the evolution of stellar luminosity and EUV flux, the initial amount of water and so on. Therefore, we focus on a change of the amount of water by the water loss and the stellar evolution and discuss the planetary evolution path from the aqua planet mode to the land planet mode. Additionally, we re-evaluate the inner edge of the HZ considering the evolution to the land planet mode.

2. Model

We consider the hydrodynamic escape of water vapor because any other hydrogen escape mechanisms cannot change the amount of water significantly. There are two modes of hydrodynamic escape: the energy-limited escape mode (Watson *et al.* 1981) and the diffusion-limited escape mode (Walker 1977). The former mode is limited by the incident solar EUV flux that exponentially decreases with the stellar age (Lammer *et al.* 2009). The latter mode is limited by the diffusion flux of water vapor in the atmosphere. This escape flux depends on the mixing ratio of water vapor in the upper atmosphere, which increases with the surface temperature. We use the relations between the mixing ratio and the incident solar flux for an aqua planet (Abe & Matsui. 1988) and a land planet (Abe *et al.* 2011) with an Earth-like atmosphere. The mixing ratio of water vapor increases as the luminosity from the central star increases with the stellar age (Gough. 1981). There is a bottleneck for the water loss. The escape flux of water should be smaller one in the energy-limited escape mode and the diffusion-limited escape mode. Therefore, in our calculation of the escape flux of water, we use the smaller flux between two modes.

Although the transition condition of the amount of water from the aqua planet mode to the land planet mode is not clear, but the transition should occur before the complete loss of water. Here, we set the transition condition as a parameter and show the case of 3-m depth in global average.

3. Results & Discussion

Figure 1 (a) shows the evolution of the amount of water in case of an Earth-size planet with 0.1 Earth's ocean initially at 0.75 AU around a solar-type star. Such a planet maintains liquid water on its surface in the aqua planet mode for 1.5Gyrs. After that, rapid water loss occurs because the mixing ratio of water vapor in the upper atmosphere increases rapidly. Therefore, such a planet losses most of its water before the onset of the runaway greenhouse, and it can evolve to a land planet and maintains liquid water on its surface for another 2.5Gyrs.

There are three key factors: the 'period of rapid escape' which is defined as the period between the onset of a rapid increase of the mixing ratio of water vapor in the upper atmosphere and the onset of the runaway greenhouse, the EUV flux from the central star on that time and the initial amount of water. An aqua planet can evolve to a land planet if most of water is lost in the period of rapid escape. Therefore, planets with initially small amount of water ($<$0.1 present Earth's ocean) tend to easily evolve to land planets. On the other hand, planets with present Earth's ocean cannot evolve to land planets.

Figure 1 (b) shows the inner edge of the HZ considering the evolution from the aqua planet mode to the land planet mode is taken into account. The planetary evolution path on figure 1 (a) is indicated by arrows on figure 1 (b). Considering the evolution to the land planet mode, the inner edge of the HZ is close to the central star than that of the classical HZ. Therefore, the initial amount of water is also important for their habitability and the inner edge of the HZ.

Additionally, we compare our results with Kopparapu *et al.* (2013). They recently improved 1-D radiative-convective, cloud-free climate model and estimated the new HZ around various types of star. For a solar-type star, they estimate the inner edge of the HZ to be 0.99 AU by the rapid water loss. However, they did not consider the initial amount of water. Therefore, an aqua planet can evolve to a land planet if most of water is lost in the period of rapid escape. Figure 2 shows the maximum and minimum amounts of

https://doi.org/10.1017/S1743921313013082 Published online by Cambridge University Press

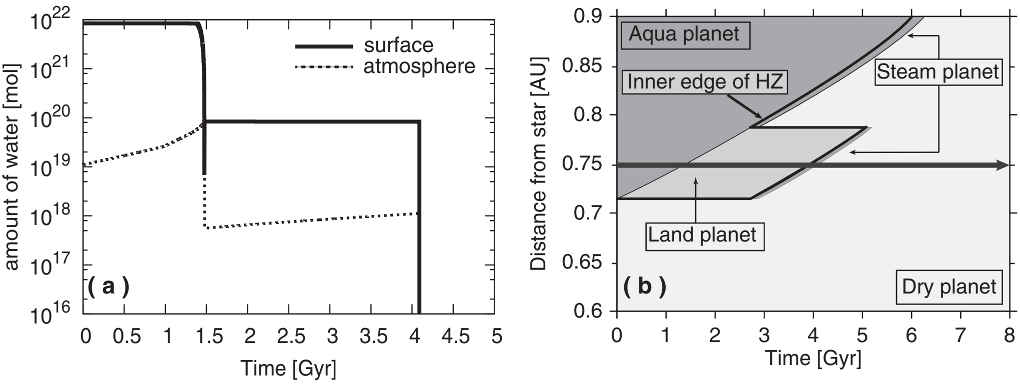

Figure 1. (a) The change of the amount of water. (b) The inner edge of the habitable zone

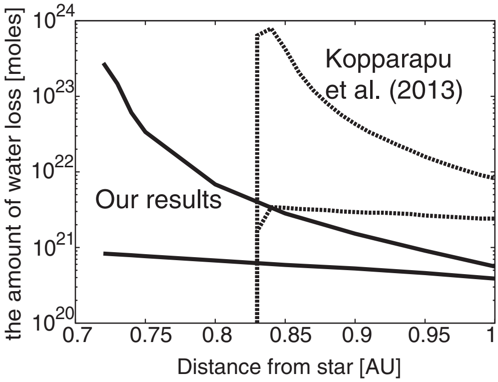

Figure 2. the limit of the initial amount of water

water loss in the period of rapid escape by using our model and results of Kopparapu *et al.*(2013). We estimate the amount of water loss in the period of rapid escape. The maximum and minimum amounts of water loss are estimated from the energy-limited escape mode and the diffusion-limited escape mode, respectively. From the results of Kopparapu *et al.* (2013), we get only the relation that the luminosity from the central star when the mixing ratio of water vapor in the upper atmosphere becomes 10^{-3}. For the diffusion-limited escape, we assume the mixing ratio of water vapor in the upper atmosphere to be 10^{-3} because the change of the diffusion-limited escape flux is unclear in Kopparapu *et al.* (2013). The minimum diffusion-limited flux is given by this value of the mixing ratio of water vapor. planets can evolve to the land planet mode if the initial amount of water is less than the amount of water loss by a rapid escape. As a result of comparison between two estimations, the initial amount of water is rarely different. However, the timing of the evolution from the aqua planet mode to the land planet mode becomes early. Additionally, the inner edge of the HZ moves over a little to a far region from the central star.

References

Abe,Y. & Matsui, T. 1988, *J Atmos Sci*, 45, 3801-3101
Abe, Y., Abe-Ouchi, A., Sleep, N. H., & Zahnle, K. 2011, *Astrobiology*, 11, 443–460
Gough, D. O. 1981, *Solar Physics*, 74, 21–34
Kasting, J. F., Whitmire, D. P., & Reynolds, R. T. 1993, *Icarus*, 101, 108–128
Kopparapu, *et al.* 2013, *ApJ*, 765, 131
Lammer, *et al.* 2009, *A&A*, 506, 399–410
Walker, J. C. G. 1977, *Evolution of the Atmosphere. MacMillan, New York*, p.164
Watson, A. J., Donahue, T. M., & Walker, J. C. G.. 1981, *Icarus*, 48, 150–166

https://doi.org/10.1017/S1743921313013082 Published online by Cambridge University Press