EVOLUTION FROM OCEAN PLANET TO LAND PLANET BY WATER LOSS; THE INNER EDGE OF HABITABLE ZONE.

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Introduction: Liquid water on the planetary surface is thought to be important for the origin and evolution of life. Habitable zone (HZ) has been defined as the region from the central star where liquid water is stable in the planetary surface. Kasting et al. [1] have estimated the width of HZ around various type of the main sequence stars for the Earth-like planets (called 'ocean planet') which possess the ocean with the present Earth's ocean mass. The inner edge of HZ is determined by the complete loss of the ocean by hydrodynamic escape. Just before the runaway greenhouse state, the mixing ratio of water vapor in the upper atmosphere rapidly increases, which causes enormous escape of water. Incident solar radiation of the inner edge of HZ around solar-like star is calculated to be about 110% of the present solar radiation at 1AU. The outer edge of HZ is determined by CO_2 condensation. Incident solar radiation of the outer edge of HZ is calculated to be about 90% of the present solar radiation at 1AU. Both of the inner and outer edges of HZ are controlled by the strong positive feedback mechanism of H_2O.

On the other hand, Abe et al. [2] have considered a hypothetical planet with very small amount of water (called 'land planet'). On a land planet, they ignore the oceans, rivers and underground water transport. Therefore, water circulation is limited in atmospheric circulation, and the distribution of ground water is completely determined by the local balance between precipitation and evaporation. Using GCM (general circulation model) they have calculated the inner and outer edges for a land planet. HZ for a land planet is located between 77% and 170% of the present solar radiation at 1AU. HZ on a land planet is about three times wider than that on an ocean planet.

According to the above two studies, the amount of water on the planetary surface is important to the width of HZ. Here, we focus on the evolution of water content on the planet by considering the water loss. If the water is efficiently lost during stellar age (~10Gy), it is a possibility that an ocean planet changes to a land planet which means that the HZ becomes wider. In this case, the ocean planet inside or outside of HZ would become habitable planets as a land planet.

Model: We consider the hydrodynamic escape of water vapor. There are two modes of hydrodynamic escape; the energy-limited mode and diffusion-limited mode. The former mode is limited by the incident solar XUV (X ray and extreme UV). We use time-dependent XUV flux [4] which exponentially decreases with the stellar age. The latter mode is limited by the diffusion of water vapor in the atmosphere [6]. The escape flux depends on the mixing ratio of water vapor in the upper atmosphere. We use the relations between the mixing ratio and incident solar flux for an ocean planet [5] and a land planet [6] with 1 atmosphere. In our calculation for water loss, we use the smaller flux between two modes.

Considering time-dependent solar luminosity [3] which gradually increases with the stellar age, we calculate the change of water content of planets with various initial water contents and distances from central star. We consider the various-sized planets with zero obliquity and eccentricity.

Although the transition condition of water content from an ocean planet to a land planet is not clear, it ought to be very small amount. Here, we set the transition condition as a parameter, and show the standard case of 3-m depth in globally average water.

Results: Figure 1 shows the evolution of water content for the case of the Earth-sized planet with initial water of 0.01-ocean mass at 0.8 AU around the Solar-like star. As the central star evolves, that is, the luminosity increases, the surface temperature and mixing ratio of water vapor in the upper atmosphere increases, which causes large escape flux of water vapor. At ~ 3.1Gyr, rapid escape of water vapor by diffusion-limited mode occurs just before runaway greenhouse state. This planet changes from the mode of an ocean planet to the mode of a land planet. Since the mixing ratio of water vapor for a land planet is very small [2], escape flux rapidly decrease. This planet keep habitable after 3.1 Gyr.

Figure 2. shows the classification map of planets after 4.5Gy for various distance from the Solar-type star and initial water content. The planets are classified into "Water planets" (liquid water on the surface), "Steam planets" (runaway greenhouse state) and "Dry planets" (no liquid water on the surface). For the case of the planets with initial high water content, as seen in Figure 2, the planets with < 0.1 ocean-mass water, which are located outside HZ for an ocean planet, possibly evolves into a habitable land planet by water loss.

Summary and Discussion: We discuss the inner edge of HZ and imaginary planetary evolutions by water loss. Ocean planets which initially possess a large amount of water possibly evolve into land planets by hydrodynamic escape of water vapor. Such planets keep habitable. For the change from an ocean planet to land planet, the following two timescales are essential. One is timescale of loss of ocean by escape. Another is timescale of evolution of central star. When the timescale of loss of water is shorter than the timescale of the evolution of central star, the ocean planets become the land planet. On the other hand, when the latter is shorter than the former, the ocean planet become runaway greenhouse state (Steam planets or Dry planets).

It's not always true that extrasolar terrestrial planets have the same amount of the present Earth's ocean mass. Our study demonstrates the possibility of the various types of habitable planets, which will be observed in the future. In this presentation, we will discuss the results for various types of stars and planetary size.

Reference: [1] Kasting, J. F., Whitmire D. P., and Reynolds, R. T. (1993). Icarus, 101, 108-128. [2] Abe et al (2010 ,prep). [3] Gough, D. O (1981) Solar Physics, vol. 74, Nov. 1981, p. 21-34. [4] Guinan, E.F., Ribas, I., 2002. Vol. 269. Astron.Soc. Pacific,SanFrancisco, pp.85-106. [5] Abe and Matsui (1986). [6] Walker (1977)

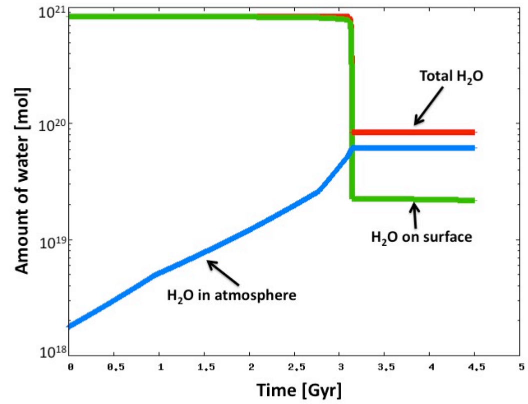

Figure 1. The time evolution of water content. The planet initially has 0.01 ocean mass and locate 0.8AU from central star. Enormous hydrodynamic escape occurs and the planet change from ocean planet to land planet at 3.1Gyr. The planet keeps habitable after 4.5Gyr.

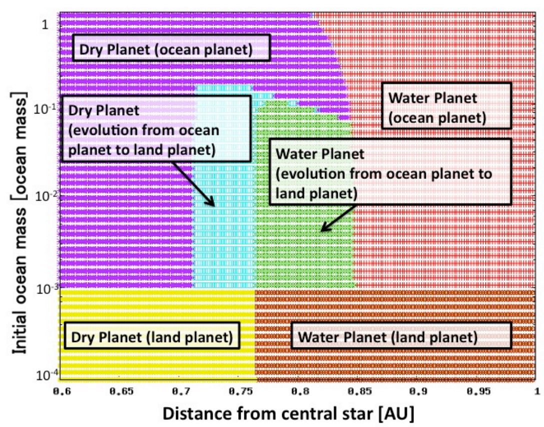

Figure 2. Classification map of planets after 4.5Gyr for various distances from the solar-type star and initial water content. Planets are classified three planetary types finally; Water planet, Steam planet and Dry planet.