# 論文の内容の要旨

## Evolution of atmosphere of terrestrial habitable planets against luminosity evolution of central stars
## (中心星光度進化に対する地球型ハビタブル惑星の大気進化)

氏 名　　小玉　貴則

Recently, many extrasolar planets have been detected and the habitability of extrasolar planets has been actively discussed. In general, it is assumed that an Earth-like planet with oceans may be a habitable planet. Such a planet is implicitly assumed an "aqua planet" (surface of a planet is covered with oceans), like the Earth. According to studies on the evolution of an aqua planet (or the early Venus), the atmosphere of such an aqua planet will be in the moist greenhouse state as the luminosity of the central star increases to a certain critical value. In the moist greenhouse state, the upper atmosphere becomes wet and a rapid water loss would occur. When the luminosity of the central star increases further, the planet becomes into the runaway greenhouse state. In the runaway greenhouse state, all of water on the planetary surface evaporates to the atmosphere, and the planetary surface would be covered with magma ocean owing to the greenhouse effect of a steam atmosphere.

On the other hand, when the amount of water on the planetary surface is very small, the evolution could be different. Such a planet with a very small amount of water is called a "land planet". Although a land planet also evolves to the runaway greenhouse state at the end of its habitability, the critical insolation for a land planet to be in the runaway greenhouse state is much higher than that for an aqua planet owing to the localization of water in high latitudes on a land planet. The distribution of surface water is strongly linked to the amount of water, hence it is suggested to be important for the evolution of a habitable planet.

To understand variety of habitable planets and their long-term evolution, I focused on the amount of water on the surface of a habitable planet and its evolution in this study. Because the amount of water on the surface of an aqua planet decreases by a rapid water loss to space in the moist greenhouse stage, an aqua planet might be able to evolve to a land planet. I investigate this possibility in Chapter 2. The relationship between the distribution of the surface water and the threshold condition of the runaway greenhouse for a land planet is also investigated in Chapter 3. Finally, based on the results, I discuss the evolution of a habitable planet in Chapter 4

Changes in the amount of water on the planetary surface and in the planetary atmosphere are estimated, considering the escape of water to space and the luminosity evolution of the central star, in order to discuss the evolution from the aqua planet to the land planet. A vertical, one-dimensional, non-gray radiative-convective equilibrium model is used to estimate the amount of water in the atmosphere, as well as a mixing ratio of water vapor in the upper atmosphere. Evolution of the luminosity and the EUV flux of the central star are considered to estimate both the diffusion-limited escape flux and the energy-limited escape flux from the planetary atmosphere in the moist greenhouse state. Two parameters are considered as the transition condition from the aqua to land planet: the amount of water on the planetary surface on the land planet (1, 5, 10% of the present Earth's ocean mass) and the amount of water in the planetary atmosphere just before the onset of the runaway greenhouse (0.1, 0.3, 0.5, 1 bar). I found that an aqua planet with a relatively small amount of water (for example, an aqua planet with 0.1 of the present Earth's ocean mass at 0.8 AU) could evolve from the aqua to land planet. Such a planet can maintain liquid water on its surface for more 2 Gyr. It is therefore suggested that a rapid water loss could result in extending the lifetime of the planetary habitability, although it has been considered as the end of the habitable world.

It is suggested that the threshold insolation for the runaway greenhouse condition strongly depends on the distribution of water on the surface of a land planet. However, the quantitative relationship between the distribution of the surface water and the threshold insolation is still not clear. The distribution of the surface water may be determined by the surface topography, the surface water flow and the transport of water vapor in the atmosphere. The limit for the latitude of water transport on the surface is therefore treated as a parameter, named the water flow limit, and the threshold insolation for the runaway greenhouse condition is estimated for various distribution of the surface water using an Atmospheric General Circulation Model (AGCM 5.4g). As a result, the climate of a water planet is divided into two regimes, the aqua planet regime and the land planet regime, due to an influence of the Hadley circulation. When the water flow limit is located in the latitude lower than the width of the Hadley circulation, the equatorward transportation of water vapor in the atmosphere occurs and the surface of the planet is covered with oceans globally. In such a case, the threshold insolation for the runaway greenhouse corresponds to that for an aqua planet. On the other hand, when the water flow limit is located in the latitude higher than the width of the Hadley circulation, the threshold insolation for the runaway greenhouse increases with an increase in the water flow limit. In this land planet regime, the threshold insolation for the runaway greenhouse changes from 130 % to 180 % of the present solar flux at the Earth's orbit. In addition, the relationship between the amount of water and the water flow limit is investigated assuming the surface topography. As a result, the critical amount of water on the surface, which divides the climate of the water planet into the aqua planet regime and the land planet regime, is estimated to be about $10^{16}$ m$^3$ (~1% of the Earth's ocean volume), considering the water flow limit derived from the relationship between the threshold insolation for the runaway greenhouse and the water flow limit, and assuming the topography of the Earth.

Finally, the evolution of a land planet is discussed. One of the unresolved questions is whether the atmosphere of a land planet evolves to the moist greenhouse state, like the atmosphere of an aqua planet does. If the atmosphere of a land planet also evolves to the moist greenhouse state, it is possible that a land planet can evolve with reducing the amount of water in the moist greenhouse stage, which results in an increase of the threshold insolation of the runaway greenhouse. In other words, a land planet can extend its habitability owing to the reduction of the water flow limit. The evolution of a planet with water on its surface is divided into three paths: evolution in only aqua planet mode, evolution from the aqua planet mode to the land planet mode and evolution in only land planet mode (Figure 1). The atmospheric features on the evolutionary paths will provide valuable information for the detection of habitable exoplanets. Observations for habitable planets in the extrasolar planetary systems, on the other hand, the results of this study could be verified in the future.

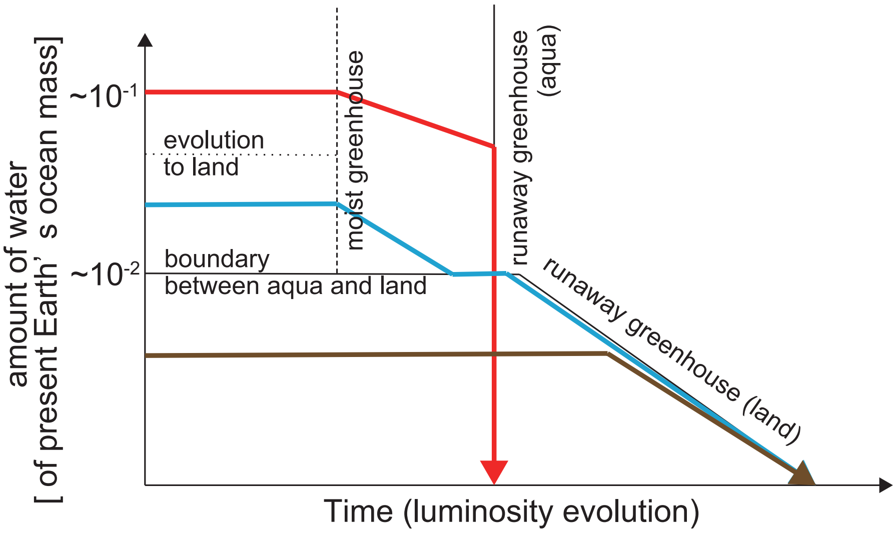


Figure 1. Evolution paths of terrestrial water planets.