論文の内容の要旨

Geochemical carbon cycle and climate of ocean terrestrial planets in the habitable zone

(ハビタブルゾーンにおける海洋を持つ地球型惑星の炭素循環と気候)

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What made the Earth habitable? This is a long-standing issue in planetary science. At present, in addition to the Earth, we have to generalize the comparative theory of planetary habitability for the Solar-system planets toward extra-solar plants because many exoplanets including similar in size to the Earth have been detected. In this doctoral thesis, we explore the climate of terrestrial exoplanets and detectability of by near-future observations in order to gain a deeper understanding of climate and habitability of terrestrial planets.

Most previous theoretical studies of planetary habitability assume Earth-like terrestrial planets characterized by active plate tectonics and coexistence with oceans and continents. They also assume that a carbonate-silicate geochemical carbon cycle (called carbon cycle hereafter) stabilizes the climate of Earth-like planets, as in the Earth, because removal of the greenhouse gas CO_2 from the atmosphere via weathering on continents strongly depends on the surface temperature. However, planet formation theories predict that Earth-like exoplanets are not necessarily abundant and the habitable zones around other stars are populated by planets retaining much more water than the Earth's oceans, meaning continental weathering never works. Thus, the carbon cycle in water-rich, continental-free planets is a crucial issue for planetary habitability.

The purpose of this doctoral thesis is to explore the effects of water amount on the planetary climate of terrestrial exoplanets in the habitable zone. To do so, we develop a new theoretical model for the carbon cycle in water-rich terrestrial planets in the habitable zone (Part 1). Furthermore, we propose a new way to verify our theoretical prediction regarding their climate features with near-future observations (Part 2).

Previous studies inferred that terrestrial planets covered globally with thick oceans (termed ocean planets) in the habitable zone have extremely hot climates, because H_2O high-pressure ice on the seafloor prevents chemical weathering and, thus, removal of atmospheric CO_2. Those studies, however, ignored melting of the high-pressure ice and horizontal variation of the heat flux from the oceanic crust. In Part 1, we develop integrated climate models of an Earth-size ocean planet with plate tectonics for different ocean masses, which include the effects of high-pressure ice melting, seafloor weathering, and the carbon cycle. We find that the heat flux near the mid-ocean ridge is high enough to melt the high-pressure ice, enabling seafloor weathering. In contrast to the previous theoretical prediction, we show that the climates of terrestrial planets with massive oceans lapse into extremely cold ones (or snowball states) with CO_2-poor atmospheres. Such extremely cold climates are achieved mainly because the high-pressure ice melting results in fixing the seafloor temperature at the melting temperature, thereby keeping a high weathering flux regardless of surface temperature. However, seafloor weathering would be limited the supply of cation from the oceanic crust. Including the supply-limit for seafloor weathering, we also find the climate of the ocean planet with a massive ocean lapses into an extremely hot one with a CO_2-rich atmosphere because seafloor weathering is ineffective in compensating massive degassing. Consequently, the ocean planets with several tens of the Earth's ocean mass no longer maintain temperate climates.

In Part 2, we explore the distinguishing between extremely hot and cold climates of ocean planets predicted in Part 1. The CO_2 abundance strongly affects the temperature of the upper atmosphere. The upper atmosphere with a low mixing ratio of CO_2 is significantly expanded. On the other hand, the Russian space telescope World Space Observatory—Ultra-violet (WSO-UV) to be launched in 2025 plans to observe exoplanets transiting in front of relatively low temperature stars (or M-type stars) with the emission lines of oxygen (OI lines), enabling us to detect expanded atmospheres. Thus, we investigate the effects of the CO_2 abundance on the absorption depth of OI lines. To do so, we develop the upper atmosphere model and transmission model, which estimates the absorption of OI lines in expanded planetary atmosphere during transit, for an ocean planet around an M-type star. We find that the atmosphere with small or moderate CO_2 abundance produces significant absorption of OI lines. Instead, the CO_2 dominant atmosphere that achieves the extremely hot climate absorbs only a small portion of stellar light. Those results suggest that the difference in planetary climate of ocean planets with massive oceans coming from the difference in planetary degassing rate is distinguishable from observations. This is a milestone for understanding what makes a habitable planet and what made the Earth habitable.