論文の内容の要旨

Theoretical study on diversity and evolution of climate of Earth-like planets in habitable zone

(ハビタブルゾーンにおける地球類似惑星の気候の多様性及び進化に関する理論的研究)

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The climate of the Earth is thought to have been warm throughout the history although the Earth is expected to be globally ice-covered owing to the low luminosity of the young Sun, assuming that the atmospheric composition is as same as that of the present Earth. This discrepancy is known as the "faint young Sun paradox". The key mechanism to resolve the paradox is the carbonate-silicate geochemical cycle which controls the atmospheric carbon dioxide and keeps the Earth warm with its negative feedback (the "Walker feedback"). However, recent studies revealed that the Walker feedback does not always work efficiently: for example, a CO_2 degassing rate of 10 times smaller than that at the present may cause the snowball Earth events. Hence, it is implied that there is a limit of application of the Walker feedback to maintain the Earth's climate warm, but the condition for the applicable limit is still unclear. In addition, global glaciations (snowball Earth events) occurred repeatedly in the Neoproterozoic, although the reason for that is uncertain. In this study, with a climate model coupled with a carbon cycle model, the limit of application for the Walker feedback mechanism of the Earth is investigated in terms of insolation (orbital semi-major axis) and a CO_2 degassing rate (index of internal activities of the Earth). In addition, the evolutionary track of the Earth is investigated based on the stellar and planetary thermal evolutions in order to reveal the reasons why

the Earth has been warm throughout the history and also the snowball Earth events occurred repeatedly at the Neoproterozoic era.

Focusing on the hypothetical Earth orbiting within the habitable zone (HZ), the climate of the hypothetical Earth with the carbon cycle is classified into three climate modes: the warm climate, snowball cycle, and warm climate cycle modes (Figure 1). In the warm climate mode, the climate is controlled by the Walker feedback mechanism, and both the balances of energy and CO_2 are achieved. The climate of the Earth at present corresponds to this climate mode.

In other climate modes, the balance of CO_2 is not achieved, hence the climate is not in a steady state. The climate of the planet in the snowball cycle mode oscillates between the warm and snowball states. This is because there is no liquid water on the planetary surface, hence CO_2 should accumulate in the atmosphere without being consumed, and the snowball state would end finally owing to the greenhouse effect of dense CO_2 atmosphere. The climate is, however, not in a steady state because the CO_2 balance is not achieved, resulting in a decrease in $p\mathrm{CO_2}$ and surface temperature; the large ice-cap instability due to the ice-albedo feedback finally occurs owing to the decrease in surface temperature, resulting in a snowball state again.

There is another climate mode: the warm climate cycle mode in which the climate oscillates between ice-free and partially ice-covered states owing to imbalance of energy budget and the positive feedback caused by H_2O atmosphere.

At the critical condition between the warm climate and snowball cycle modes, $p\mathrm{CO_2}$ increases with a decrease in the insolation while the globally-averaged surface temperature stays around $\sim 273\,\mathrm{K}$. This relation between the insolation and the critical $p\mathrm{CO_2}$ depends mainly on the relation between $p\mathrm{CO_2}$ and the planetary radiation, which determines the critical CO_2 degassing rate between the warm and snowball cycle modes. Hence, the critical CO_2 degassing rate increases with a decrease in insolation, and the condition under which the Earth is in the warm climate mode is limited only to the part of the HZ especially when the CO_2 degassing rate is low: for example, when the CO_2 degassing rate is as much as that of the present Earth, more than 0.8 times of the present insolation is necessary for the Earth to be in the warm climate mode (Figure 1).

In addition, there are two different outer limits of the HZ: one is the minimum insolation at which the climate of the Earth is able to be in the warm climate mode, and the another is the minimum insolation at which the climate of the Earth is able to recover from the snowball state. These two different limits are caused by the difference in the surface albedos of the planet of the warm and snowball state, and a planet whose insolation is between these limits has hysteresis in its climate mode.

The Earth was in the warm climate mode owing to high CO_2 degassing rate which may relate to high mantle temperature in the past while the insolation was lower then (Figure 1). The Earth has been in the warm climate mode during the history because a decrease in a CO_2 degassing rate due to the cooling of the planetary interior has been compensated by an increase in the insolation due to the evolution of the Sun (Figure 1). Continental growth (i.e., an increase in the continental size with time) would have been responsible for the warm climate mode Earth in the past. Considering the hypothetical Earth of which orbit is farther from the Sun than the real Earth, the warm climate has been maintained for the first several giga years owing to initially high CO_2 degassing rate, but it shifts to the snowball cycle mode owing to the decrease in the CO_2 degassing rate with time. The timescale of the shift to the snowball cycle mode depends mainly on the evolution of the CO_2 degassing rate, in other words, the evolution of the planet. This timescale is, therefore, roughly the same for the planets with different orbital semi-major axis in the outer HZ, and even when a type of the central star is different (i.e., the timescale of the stellar evolution is different). In the snowball cycle mode, the hypothetical Earth is more likely in the snowball state than in the warm climate state; therefore, the hypothetical Earth (i.e., an extra-solar Earth-like planet) in the outer HZ around old star is supposed to be observed as a snowball planet.

The Earth has been in the warm climate mode during its history as explained above. However, a certain perturbation to the carbon cycle system could have moved the Earth's climate to the snowball cycle mode. Comparing the critical condition between the warm and snowball cycle modes with the evolutionary track of the climate of the Earth on the diagram of the insolation and the CO_2 degassing rate, it is about 700 million years ago, which corresponds to the Neoproterozoic era in the Earth's history, that the conditional distance to the snowball cycle mode becomes minimum throughout the evolution of the Earth. This might explain the reason why the snowball Earth events repeated twice within a relatively short period of time ($<$ 100 million years) during the Neoproterozoic, although, besides the Neoproterozoic snowball Earth events and another one event in the Paleoproterozoic, there is no other snowball Earth event occurred during the whole history of the Earth.

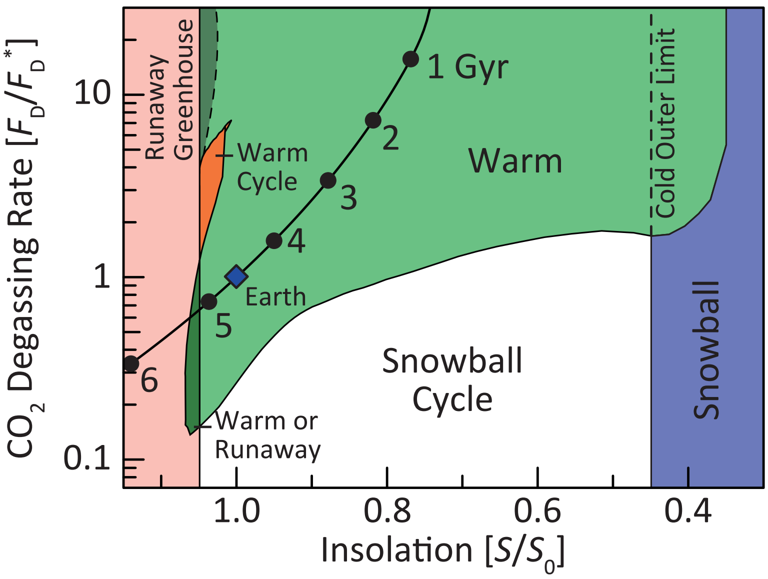

Figure 1: Climate modes for the Earth as a function of insolation and a CO_2 degassing rate and an evolutionary track of the climate of the Earth orbiting at 1 AU from the Sun. Within the habitable zone (i.e. the region between the runaway greenhouse and snowball climate modes), there are three climate modes: warm climate, snowball cycle, and warm climate cycle modes. The evolutionary track suggests that the Earth has been in the warm climate mode owing to the high CO_2 degassing rate. According to the results, the Earth is the most susceptible to global glaciations (goes into the snowball cycle mode) at 4 Gyr (i.e., the Neoproterozoic era) when the snowball Earth events actually occurred repeatedly.