Outer limit of the habitable zone considered in terms of climate jump from snowball state

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It has been considered that an outer limit of the habitable zone (HZ) is determined by insolation bellow which water on a planet should freeze over, while the influence of formation of CO_2 clouds has remained unknown. However, it has not been studied how does a planet initially outside of the HZ and in the snowball climate state evolves with an increase in insolation of the central star. It is important because such a snowball planet could evolve to the warm climate state when the insolation increases to a critical value, but it may be different from the condition of the outer limit of the HZ described above owing to the difference in the planetary albedos of the warm and snowball planets. In this study, we investigate the climatic evolution of an Earth-like planet outside of the HZ to reveal the condition of the outer limit.

The insolation above which a snowball planet shifts to the warm state is estimated to be 0.46 S_0 (S_0: present solar flux at the Earth's orbit). We call it hereafter a "cold outer limit". It is larger by 0.1 S_0 than the insolation bellow which water on a planet should freeze (this corresponds to the traditional outer limit of HZ, and we call it a "warm outer limit"). Both outer limits are controlled by the maximum greenhouse effect of CO_2, and the difference is owing to the difference in the planetary albedo. The condensation of CO_2 does not affect both limits in this calculation. Although it highly depends on the efficiency of meridional heat transport: if the efficiency of the meridional heat transport is low, the cold outer limit is determined by the insolation under which CO_2 condensates as indicated in the previous works. For a planet with low efficiency of the meridional heat transport (e.g., owing to high rotation rate and/or thin atmosphere), the cold outer limit is controlled by condensation of CO_2; on the other hand, for a planet with high efficiency of the meridional heat transport (e.g., owing to low rotation rate and/or thick atmosphere), the cold outer limit is controlled by the maximum greenhouse effect of CO_2 with high planetary albedo. In both cases, the insolation of the cold outer limit is higher than that of the warm outer limit.

Then, the increase in stellar evolution and the decrease in a CO_2 degassing are considered as a driving force of the climatic evolution of a planet. We found that a planet initially in the HZ and the warm climate state owing to the initial high CO_2 degassing rate tends to remain the warm state. However, a planet outside of the HZ and initially in the snowball state shifts to the warm climate state when the insolation it receives becomes larger than the cold outer limit. However, if the increase in the stellar luminosity is slow relative to the decrease in the CO_2 degassing rate (e.g., for the case of a low-mass star), the decrease in the CO_2 degassing rate results in the planet initially inside the HZ shifting from the warm state to the snowball state, although the insolation increases with time. In that case, the planet is orbiting inside the warm outer limit but outside the cold outer limit, and because the cold outer limit moves outward with time, the planet will be in the HZ again. In other words, the outer limit of the HZ shifts inward. Hence, the outer limit of the HZ is determined by the initial location of the warm outer limit and the outward shift of the cold outer limit due to the increase in the stellar luminosity. In this respect, the cold outer limit, instead of the traditional warm outer limit, should be treated as the outer limit of the HZ.

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