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Effects of Orbital Eccentricity on Habitability of Earth-like Extra-solar Planets with Carbon Cycle

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In this study, we systematically investigate the climate of the planets with varying orbital eccentricity and semi-major axis, and with carbonate-silicate geochemical cycle. We adopt a one-dimensional energy balance climate model and weathering model by Walker et al. (1981). We try to find conditions for the Habitable zone (HZ) of eccentric planets, and clarify the factors to determine the Habitable zone of eccentric planets. The results shows that there are three possible climate phases, namely Ice-free, Ice-cap, and Snowball phase, and nine climate modes, namely Runaway Greenhouse (RG), Ice-Free (IF), Seasonally Ice-cap (SIC), Ice-cap (IC), Seasonally Snowball/Ice-free (IF), Seasonally Snowball (SSB), Snowball (SB), Cyclic Snowball (CSB), and CO 2 Condensation (CO2C) modes. The term 'phase' is defined here as a transient state of climate, and the term 'mode' as an annual or long-term state of climate. The HZ is consist of the regions where a planet has liquid water on its surface, i.e. IF, SIC, IC, SSI, and SSB mode. The inner boundary of IC mode and the lower boundary of SSB, which are both the limits of the HZ, are found to be determined by annual mean insolation and perihelion distance, respectively.

If the heat capacity was very large, surface temperature would be averaged over a long period. It means that the climate of the planet would be affected by the annual mean insolation. This is why the inner boundary of IC is determined by annual mean insolation because of large heat capacity of IC mode planets.

On the other hand, if the heat capacity was very small, the temperature would follow the variation of insolation instantly. It means that the variation of the distance between from the central star, i.e. the perihelion and aphelion distance, would determine the climate of the planet. This is why the lower boundary of SSB is determined by perihelion distance because of the small heat capacity of SSB mode planets.

It appears that carbonate-silicate geochemical cycle also affects on the width of the HZ due to negative feedback effect which stabilizes the climate. When carbon cycle is considered, the width of the HZ becomes broader than when it is not considered.

The eccentric planets with large semi-major axis are habitable even in the early stage of stellar evolution. On the other hand, planets with small semi-major axis withdraw from the HZ in earlier stage of stellar evolution.

We, therefore, conclude that planets with large semi-major axis and high eccentricity should to be in the HZ for a long time.

Keywords: habitability, orbital eccentricity, carbonate-silicate geochemical cycle, EBM