LIMIT CYCLES COMPLICATE THE OUTER EDGE OF THE HABITABLE ZONE.

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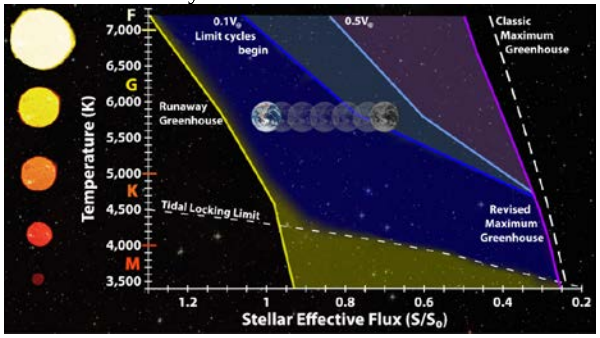
Summary: The liquid water habitable zone (HZ) describes the orbital distance at which a terrestrial planet can maintain above-freezing conditions through regulation by the carbonate-silicate cycle. Calculations with climate models predict that the inner edge of the HZ is limited by water loss through a runaway greenhouse, while the outer edge of the HZ is bounded by the maximum greenhouse effect of carbon dioxide. This classic picture of the HZ continues to guide interpretation of exoplanet discoveries; however, recent calculations have shown that terrestrial planets near the outer edge of the HZ may exhibit other behaviors that affect their habitability.

Here we discuss new results from climate models to understand the stellar environments most likely to support a habitable planet. Our energy balance climate model calculations summarized below show the conditions under which planets in the outer regions of the habitable zone should oscillate between long, globally glaciated states and shorter periods of climatic warmth, known as ‘limit cycles.’



These calculations [1] show that the net volcanic outgassing rate is a critical factor that determines the susceptibility of a planet to limit cycling. ($V_{\oplus}$ is present-day outgassing.) Earth-like planets that exhibit this type of limit cycling behavior cannot maintain permanent surface liquid water and may be inhospitable to complex life. Limit cycles may likewise provide an explanation for fluvial features on early Mars, which orbits near the edge of the HZ [2].

Dependence on Spectral Class: The carbonate-silicate cycle regulates atmospheric CO_2 on geologic timescales through the weathering of silicate rocks into carbonate rocks, balanced by outgassing of CO_2 from volcanoes. Silicate weathering slows down as temperature decreases, which allows an Earth-like planet to accumulate a dense CO_2 atmosphere at lower levels of instellation, such as toward the outer edge of the HZ. But silicate weathering is also enhanced in the presence of a dense CO_2 atmosphere, which can cause the rapid draw-down of CO_2 and loss of greenhouse warming. This suggests that some planets within the conventional HZ may actually be caught in such a cycle where warm conditions come only briefly between long episodes of global glaciation.

We develop a model that allows us to determine the limit cycle boundaries relative to the conventional liquid water HZ for different stellar spectral types. Our energy balance model (EBM) calculations improve upon previous work by Menou [3] and Kadoya & Tajika [4,5] by implementing an updated parameterization of radiative transfer as well as including the effect of CO_2 condensation and the impact of seafloor weathering.

Water ice is highly reflective at visible wavelengths, but becomes an increasingly efficient absorber at longer, near-infrared wavelengths. Ice-albedo feedback is therefore greater for planets around F stars than it is for planets around K and M stars because F stars emit a greater percentage of their radiation at visible wavelengths. Planets in F-dwarf systems are more susceptible to limit cycles than those around G-dwarfs, while planets orbiting K- or M-dwarfs manage to avoid limit cycles altogether.

Weathering on an Abiotic Planet: Another critical factor in determining the onset of limit cycles in the HZ is the partial pressure of CO_2 in soil that results from the long-term balance between atmospheric and soil CO_2 . Land plants sequester CO_2 in soil and accelerate weathering compared to an abiotic environment. If we consider a thought experiment where all of life were to suddenly vanish, then CO_2 in the atmosphere should increase until the atmospheric and soil (regolith) partial pressures were equal. This implies that an abiotic Earth should have a higher value of atmospheric CO_2 than Earth today. Our EBM estimate of the abiotic Earth temperature is higher than predicted by Menou [3] because we have tuned our model to the present-day partial pressure of CO_2 in soil.

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