Temporal entry into habitable zone for Earth-like planets J. Seales and A. Lenardic, Department of Earth, Environmental and Planetary Science, Rice University, Houston, TX.

Introduction: The interplay of solar and internal energy determines how a planet's surface temperature evolves. A star brightens with age, delivering more incident flux to the surface of aging planets, which considered alone would increase surface temperature. The decay of radiogenic elements -- the internal energy source -- heats the planetary interior. The amount of heat produced decays exponentially as the planet ages, leading to secular cooling of the interior. Warm planetary interiors move more quickly and transfer volatiles more efficiently between the surface and interior reservoirs. Volatiles such as water and CO2 act as greenhouse gasses. At a fixed point in time, increasing the amount of greenhouse gasses in the atmosphere warms the surface. At every point in time, then, a particular balance between solar and internal energy must exist for the surface to host water.

Geological evidence suggests that liquid water has existed on Earth's surface for billions of years [1]. We do not know the areal extent of that water. We do suspect that an average global surface temperature above 273 K would allow for the widespread existence of water. Pondering this sparked the question we seek to answer here: *For a distribution of planets that are similar to Earth – similar in terms of mass, size, composition and age – what are the temporal bounds for when the average global surface temperature of those planets rise above the liquid water threshold (i.e., enter the habitable zone)?*

Methods: To address our motivating questions, we coupled together process models and observational constraints. A mantle thermal history module drives the model. We required the thermal history model match geological proxy data on Earth's thermal history ([2, 3]), enforcing the "*planets that are similar to Earth"* aspect of our motivating question *but also allowing for a potential range that is associated with uncertainties inherent to observational constraints on planetary cooling paths*. The models allowed for: cycling of volatiles, namely water and CO2, between the interior and surface; the temperature buffering feedback associated with carbonate-silicate weathering coupled with a climate model; and an increase in solar luminosity with time. These aspects introduce no new novelty but mimic previous habitability studies (e.g., [4,5,6]).

Novelty entered our study through the thermal history module. We assumed plate tectonics operated over Earth's history but allowed for any variations in plate tectonic efficiencies associated with different hypotheses regarding the global energetics of plate tectonics – in particular, different assumptions as to forces that resist plate motions. All the hypotheses could satisfy Earth's thermal history data within data and model uncertainties. The different hypotheses resulted in a range of thermal paths, transferring volatiles at different rates. These rates propagated through the coupled models, eventually affecting surface temperature. We ran an ensemble of models to produce temporal uncertainty bounds for the evolution of surface temperature.

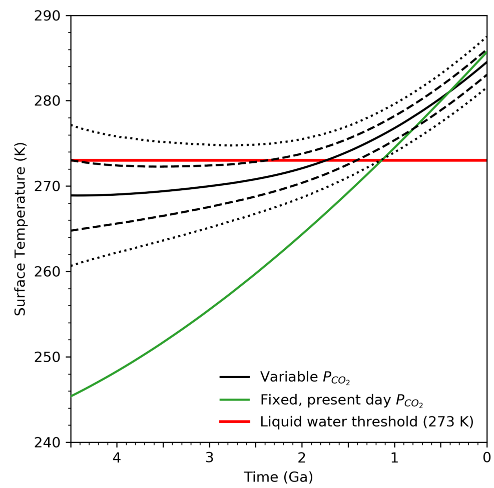

Figure 1: Temporal uncertainty window of surface temperatures that match Earth's thermal history data.

Results: Figure 1 shows the uncertainty in surface temperature over the lifetime of planets similar to Earth. As a definition, we will consider any planet with a surface temperature exceeding 273 K - they have widespread liquid water - to have entered the habitable zone (HZ). Some planets always reside in the HZ. Other planets begin warm enough to host liquid water but cannot maintain it over their entire history. For this subset of planets, solar and internal energy begin in the proper balance. Internal energy decays, cooling the interior. Volatile transfer rates drop. Solar energy does not rise quickly enough to offset the decrease in atmospheric greenhouse gasses, dropping surface temperature below 273 K. After a long enough delay, solar energy rises quickly enough to offset decaying radiogenics; surface temperature rises back above 273 K And continues to rise until the present day. The third subset of planets begin too cool - internal energy cannot drive sufficiently high volatile transfer rates. Like those that began warm enough but cooled, these to eventually entered the HZ, even if only in the past billion years.

Discussion Our results suggest that planets may enter the HZ over a window spanning billions of years. Lehmer et al. [7] also found variance in surface temperature, using point estimates rather than temporal models. Though we use different modeling methodologies and different modules within our models, overlap exists within our results. This encourages us of our studies robustness. We have also considered the effect of large fluctuations within the interior model. Such models have variable long term surface temperature trends with intermittent states of successive HZ exit-entry cycles.

Our broad conclusion is this: *planets that evolved and behaved similarly to Earth may have existed in the HZ for billions of years; may have only recently entered it; or may have oscillated into and out of it.* These nonunique outcomes occur because of the balance between solar and internal energy and the operative internal dynamics that tap internal energy. Better understanding the relative influence of the two energy sources and how internal energy is tapped may produce a better understanding of the range of environments that may emerge on planets similar to Earth in terms of bulk planetary properties.

References:

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