

Continuous Habitable Zones: Pairing a GCM and Bayesian Framework to Predict Habitable Zone Evolution

Austin Ware¹, Nancy Y. Kiang², and Patrick Young¹

¹School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287 USA

²NASA Goddard Institute for Space Studies, New York, NY 10025 USA

In the near-future, new space telescopes like JWST, LUVOIR, and HabEx will begin attempting to characterize the atmospheres of potentially habitable planets. This will require a significant amount of time and resources for even a single planet, which makes it essential to prioritize observations by those most-likely to have detectable life. Here we present a Bayesian method to estimate the probabilities that specific exoplanets are currently in the 2 Gy continuous habitable zone (CHZ₂) the approximate time it took life on Earth to significantly oxygenate the atmosphere. We introduce the use of statistics of a 3D planetary general circulation model (GCM) perturbed parameter ensemble (PPE) to estimate these probabilities, replacing prior 1D model estimates.

In prior work (Truitt et al., 2020), by considering the orbital radius of a potentially habitable planet and comparing measured host star properties to those from stellar evolution models, they fit a habitable zone (HZ) evolution model and determine the probability that a given planet is in CHZ₂. They used only the measured stellar mass and metallicity to constrain the fit to habitable zone models over the full main sequence lifetime. We have added a stellar age prior to the Bayesian calculation, allowing us to determine the current probability that a specific radius is in the CHZ₂ for ≥ 2 Gy by considering the current age of the star, the time at which a telescope would observe it.

We first used this Bayesian method, relying on the HZ definitions from Kopparapu et al. (2013, 2014), to determine the probability that 9 potentially habitable exoplanets, as well as Venus, Earth, and Mars, are currently in the CHZ₂, the results of which have been submitted for publication. A sample of these results are shown in Figure 1 for Venus, Earth, and Mars with and without the age prior, as well as for Kepler-442b. Kopparapu et al. (2013, 2014) used a 1D cloud-free radiative-convective climate model to determine the inner and outer edge of the HZ for a 0.1, 1, and 1.5 M_⊕ planet as well as a Recent Venus/Early Mars optimistic case. These models have been widely used in the exoplanet community and offer exact definitions for the inner and outer edge of the HZ. Although 1D models benefit from their relative simplicity and fast equilibration times, they are unable to properly account for

clouds, surface variations, atmospheric and oceanic heat transport, and orbital variables that would lead to uncertainty in habitability estimates. For these reasons, general circulation models (GCM) present a means to more rigorously constrain the variability of habitable atmospheres.

We have incorporated a new HZ model using results from Kiang et al. (2022 (in prep)). The authors use the ROCKE-3D GCM (Way et al., 2017) to model a PPE of land-planet atmospheres. They randomly sample 11 variables, including stellar effective temperature (T_{eff}), instellation (S_{0X}), CO₂ pressure, and additional planetary orbital, atmospheric, and surface parameters, for Earth-size planets in circular orbits. By performing a multivariate regression on the output model atmosphere values, they provide predictive equations with uncertainty estimates of the planetary surface temperature (T_{surf}) in terms of T_{eff} and S_{0X} , with other perturbed parameters imposing uncertainties in those predictions. Using outputs from the Tycho stellar evolution models, we use these equations to model T_{surf} as the star evolves. Excluding the planetary parameters in the regression quantifies their role as unknowns for exoplanets observed with near-term missions, providing an associated standard error for each regression coefficient. This enables us to propagate an error through the Bayesian HZ model and place confidence bounds on the probability of any given orbital radius being in the CHZ₂. The results of this analysis demonstrate a framework using GCM PPE's to prioritize future observations.

References:

- Kiang, N. Y., Reto, R., Colose, C., et al. 2022 (in prep), To be submitted to ApJ
- Kopparapu, R. K., Ramirez, R. M., SchottelKotte, J., et al. 2014, ApJ, 787, L29, doi: 10.1088/2041-8205/787/2/L29
- Kopparapu, R. K., Ramirez, R., Kasting, J. F., et al. 2013, ApJ, 765, 131, doi: 10.1088/0004-637X/765/2/131
- Truitt, A. R., Young, P. A., Walker, S. I., & Spacek, A. 2020, AJ, 159, 55, doi: 10.3847/1538-3881/ab4e93
- Way, M. J., Aleinov, I., Amundsen, D. S., et al. 2017, ApJS, 231, 12, doi: 10.3847/1538-4365/aa7a06

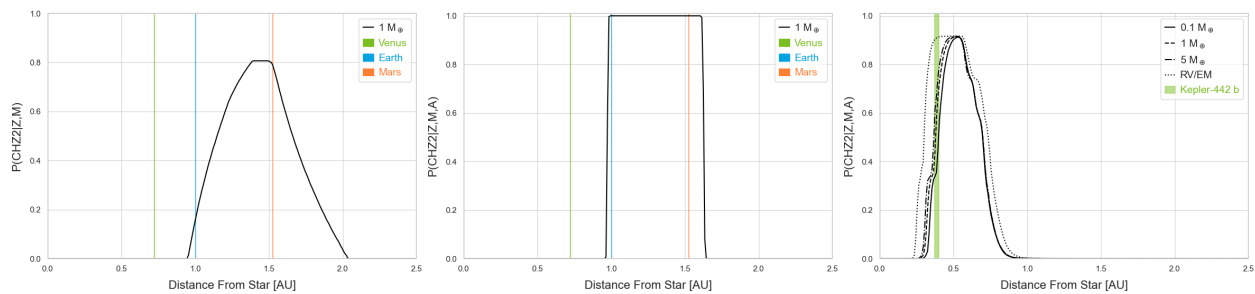


Figure 1: $P(\text{CHZ}_2)$ for the Sun without age (left), with age (middle), and for Kepler-442 with age (right).