Continuous Habitable Zones: Using Bayesian Methods to Prioritize Characterization of Potentially Habitable Worlds

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Abstract

The number of potentially habitable planets continues to increase, but we lack the time and resources to characterize all of them. With ∼30 known potentially habitable planets and an ever-growing number of candidate and confirmed planets, a robust statistical framework for prioritizing characterization of these planets is desirable. Using the ∼2 Gyr it took life on Earth to make a detectable impact on the atmosphere as a benchmark, we use a Bayesian statistical method to determine the probability that a given radius around a star has been continuously habitable for 2 Gyr. We perform this analysis on nine potentially habitable exoplanets with planetary radii <1.8 \( R_\oplus \) and/or planetary masses <10 \( M_\oplus \), around nine low-mass host stars (∼0.5–1.1 \( M_\odot \)) with measured stellar mass and metallicity, as well as Venus, Earth, and Mars. Ages for the host stars are generated by the analysis. The technique is also used to provide age estimates for 2768 low-mass stars (0.5–1.3 \( M_\odot \)) in the TESS Continuous Viewing Zones.

Unified Astronomy Thesaurus concepts: Interdisciplinary astronomy (804); Stellar properties (1624); Habitable planets (695); Catalogs (205); Habitable zone (696); Exoplanets (498); Stellar evolutionary tracks (1600); Stellar evolutionary models (2046); Stellar evolution (1599); Astrobiology (74); Stellar ages (1581); Bayesian statistics (1900)

Supporting material: machine-readable table

1. Introduction

The search for habitable worlds is at the forefront of astronomy and astrobiology. Over 4000 currently confirmed exoplanets and over 5000 TESS candidates (Ricker et al. 2014) are currently cataloged. It is now known that exoplanets are fairly common in the habitable zones (HZs) of Sun-like and M-type stars (e.g., Tarter et al. 2007; Batalha et al. 2011; Petigura et al. 2013; Dressing & Charbonneau 2015; Bryson et al. 2020), and rocky planets have been found inside HZs (e.g., Gillon et al. 2017; Dittmann et al. 2017; Bryson et al. 2021). Preliminary target lists have been mooted for NASA direct imaging missions: HabEx (Gaudi et al. 2020), LUVOIR A/B (The LUVOIR Team 2019), and Starshade Rendezvous (Seager et al. 2019). Therefore, it is now important to quantitatively characterize these known and potential planetary systems in terms of potential for habitability. The large number of theoretical and observational uncertainties mean that any given planet can only be assigned a probability that it is within the HZ and has been for some amount of time. With many known HZ planets, and additional HZ planets likely to be discovered by current and future missions, a robust statistical framework with estimates of as many contributing probability distributions as possible is desirable.

Each system with planets inside the HZ is of interest due to the potential for the emergence of life. However, we assume that life’s ability to establish itself relies largely on the stability of the planet’s environment (e.g., McKay 2014; Dong et al. 2018). We therefore need to know how long a planet has resided within the HZ to accurately predict the likelihood of life emerging and making a detectable impact on the planet’s environment. Determining the length of time a planet spends in the HZ is difficult due to the various uncertainties in the actual definition of the HZ and in the characterization of the planetary system. Using the time it took for life on Earth to significantly alter the atmosphere as a benchmark, we can use a Bayesian method to determine the likelihood that a planet in a given system will spend a similar amount of time in the continuous habitable zone (CHZ).

Previous work has shown that life on Earth made a detectable impact on the atmosphere after ∼1–2 Gyr following the Earth’s formation (Kasting et al. 1993; Brocks et al. 1999; Kopp et al. 2005; Anbar et al. 2007; Crowe et al. 2013), with the Great Oxidation Event (GOE) occurring around 2 Gyr following formation (Summons et al. 1999; Kasting & Catling 2003; Holland 2006). Following the work of Truitt et al. (2015), Truitt & Young (2017), and Truitt et al. (2020), we therefore define the orbital area around a host star that will remain habitable for at least 2 Gyr, here called the 2 Gyr continuous habitable zone (CHZ2), as a conservative estimate of the potential habitability of planets in the system across the entire main sequence. More importantly, for specific planets, it is necessary to determine whether they have already spent 2 Gyr in the HZ. We acknowledge that different timescales could be adopted considering the HZ lifetimes of planets around various stellar types (Rushby et al. 2013), but using Earth’s evolutionary history is a useful starting point in order to narrow down the list of potentially habitable planets. Different timescales can also be adopted considering the history of disequilibrium chemistry in the Earth’s atmosphere. As far back as the Archean eon (4.0–2.5 Ga), likely levels of biogenic CH4 spurred detectable disequilibrium chemistry...
habitability potential of the local region of the galaxy. The method also enables rapid characterization of future discoveries in the working angles of HabEx and LUVOIR target stars. We use stellar mass, metallicity, and age, with their associated uncertainties, as our observational priors. Because stellar ages are not known for many systems, we also develop an algorithm to determine best-fit model ages, generated using the Tycho database of stellar evolution models, for potentially habitable systems. We compare best-fit model ages for the sample of nine potentially habitable exoplanet host stars to known ages and perform the CHZ analysis. As an addition to this work, we determine best-fit ages for a sample of 2768 TESS Continuous Viewing Zone (CVZ) F, G, K, and early-M stars between 0.5–1.3 $M_\odot$. Future work includes expanding this Bayesian method to include additional stellar and planetary properties and testing various HZ model prescriptions.

2. Methods

2.1. Sample Selection

We chose a sample of nine potentially habitable exoplanets around host stars approximately 0.5–1.1 $M_\odot$ with the lower limit determined by the current lower-mass limit on the Tycho Stellar Evolution Catalog. Parameters for the sample of exoplanets are listed in Table 1 and the associated host star parameters are listed in Table 2. The planets have radii $<1.8 \, R_\oplus$ and/or masses $<10 \, M_\oplus$, putting them within the optimistic range for rocky planets. The upper radius limit for rocky planets is adopted from Fulton et al. (2017) and Thompson et al. (2018). $1.8 \, R_\oplus$ is the approximate center of the 1.5–2.0 $R_\oplus$ gap between rocky (“super-Earth”) and gaseous (“mini-Neptune”) planets, indicating an optimistic threshold. For candidates with mass measurements, we adopt the upper mass limit derived from the planetary mass–radius relation for rocky cores from Zeng et al. (2016), $M = R^{1.37}$. Assuming the above upper radius limit of 1.8 $R_\oplus$, we determine a value of $\sim 9 \, M_\oplus$ and round up to 10 $M_\oplus$.

All nine planets have installation values within the optimistic recent Venus (RV) inner habitable zone (IHZ) and early Mars (EM) outer habitable zone (OHZ) boundaries for their system, calculated using the equations defined in Kopparapu et al. (2013) and discussed in Section 2.3. From an HZ perspective, these are high-priority candidates for spectral characterization.
### 2.2. Tycho Stellar Evolution Catalog

We use the stellar evolution code Tycho (Young & Arnett 2005) to expand the catalog of evolutionary tracks in Truitt et al. (2015) and Truitt & Young (2017). Tycho is a 1D stellar evolution code that utilizes a hydrodynamic formulation of the stellar evolution equations. Tycho contains OPAL opacities (Alexander & Ferguson 1994; Iglesias & Rogers 1996; Rogers & Nayfonov 2002), utilizes a combined OPAL and Timmes equation of state (Timmes & Arnett 1999; Rogers & Nayfonov 2002), gravitationally induced diffusion (Thoul et al. 1994), general relativistic gravity, automatic re zoning, and an adaptable nuclear reaction network paired with a sparse solver. Low-temperature (∼2400 K) opacities, which include dust grain opacities, were added in Truitt & Young (2017) and are based on Ferguson et al. (2005) and Serenelli et al. (2009). Tycho uses an adaptable 177 element network up to 74 Ge that is utilized throughout the evolution. The network uses REACLIB rates (Angulo et al. 1999; Rauscher & Thielemann 2000; Iliadis et al. 2001; Wiescher et al. 2006), weak rates from Langanke & Martínez-Pinedo (2000), and screening from Graboske et al. (1973). Mass loss is included, but is trivial for the mass range considered in this work. Neutrino cooling due to the Urca process and plasma processes is included. Turbulent convection is defined via a hydrodynamic formulation (Meakin & Arnett 2007; Arnett et al. 2009, 2010; Arnett & Meakin 2011) based on 3D, well-resolved simulations of convection between stable layers. Unlike stellar evolution codes relying on mixing-length theory, Tycho has no free convective parameters (i.e., “convective overshoot”).

The catalog currently contains models between 0.5 and 1.3 $M_\odot$, with metallicities that fall between 0.1 and 3.0 $Z_\odot$. The metallicity models are in steps of 0.1 $Z_\odot$ between 0.1 and 1.5 $Z_\odot$ and steps of 0.25 $Z_\odot$ between 1.5 and 3.0 $Z_\odot$. We added a finer grid of mass models, in steps of 0.05 $M_\odot$ between 0.5 and 1.0 $M_\odot$. The mass models are in steps of 0.1 $M_\odot$ between 1.0 and 1.3 $M_\odot$. We use these models in Section 2.3 to determine the HZ boundaries over the evolution of the star. The catalog also varies in [O/Fe] between 0.44x, 1.0x, and 2.28x [O/Fe]$_e$ for the full metallicity range. These models are included in Section 2.5 when fitting the ages for stars.

| Stars          | $M/M_\odot$ | $M$ References | $T_{eff}$ (K) | $T_{eff}$ References | $\log(L/L_\odot)$ | $L$ References$^a$ | (M/H) | (M/H) References  |
|---------------|-------------|----------------|---------------|----------------------|-------------------|-------------------|-------|------------------|
| Kepler-1455   | 0.5200$^{+0.038}_{-0.030}$ | 1 | 3899 ± 78 | 2 | −1.233$^{+0.056}_{-0.081}$ | 2(R,T) | −0.21 ± 0.11 | 3     |
| Kepler-438    | 0.544$^{+0.028}_{-0.043}$  | 1 | 3748 ± 112 | 4 | −1.55$^{+0.142}_{-0.138}$ | 4 | 0.16 ± 0.14 | 4     |
| KIC-7340288   | 0.578$^{+0.028}_{-0.010}$ | 5 | 3949$^{+8}_{-12}$ | 5 | −1.190$^{+0.008}_{-0.110}$ | 6 | −0.31 ± 0.14 | 7     |
| Kepler-441    | 0.573 ± 0.026  | 1 | 4340 ± 87 | 8 | −1.06$^{+0.053}_{-0.053}$ | 8(R,T) | −0.58 ± 0.15 | 1     |
| Kepler-442    | 0.613 ± 0.03  | 1 | 4402 ± 88 | 8 | −0.86$^{+0.053}_{-0.053}$ | 8(R,T) | −0.37 ± 0.1 | 4     |
| HD 40307      | 0.71 ± 0.02  | 9 | 4827 ± 44 | 10 | −0.64$^{+0.012}_{-0.011}$ | 11 | −0.25 ± 0.029 | 10    |
| Kepler-692    | 0.727$^{+0.029}_{-0.009}$ | 1 | 4859 ± 97 | 8 | −0.59$^{+0.052}_{-0.052}$ | 8(R,T) | −0.57 ± 0.04 | 12    |
| Kepler-1544   | 0.743$^{+0.030}_{-0.030}$ | 3 | 4852 ± 97 | 8 | −0.60$^{+0.052}_{-0.052}$ | 8(R,T) | −0.08 ± 0.1 | 3     |
| Kepler-452    | 1.070$^{+0.064}_{-0.064}$ | 13 | 5772$^{+3}_{-13}$ | 13 | 0.089$^{+0.062}_{-0.067}$ | 8(R),13(T) | 0.23 ± 0.04 | 13    |

Note. $^a$ (R,T) indicates the value calculated using the referenced radius and effective temperature.

References. (1) Mathur et al. (2017); (2) Thompson et al. (2018); (3) Torres et al. (2017); (4) Torres et al. (2015); (5) Kunimoto et al. (2020); (6) Stassun et al. (2019); (7) Gaidos et al. (2016); (8) Berger et al. (2018); (9) Bonfanti et al. (2016); (10) Valenti & Fischer (2005); (11) Sousa et al. (2008); (12) Borucki et al. (2013); (13) Johnson et al. (2017).

While future direct detection missions such as HabEx and LUVOIR will concentrate on Sun-like stars, virtually all of the simulated HZ planet detections for TESS are around M-type and late K-type stars (Sullivan et al. 2015; Barclay et al. 2018). There is then significant value in including host stars below 0.5 $M_\odot$. We will expand this catalog further and include stars down to 0.1 $M_\odot$ in a future paper.

### 2.3. Habitable Zone Models

Tycho outputs information on stellar surface quantities for each time step of the evolution. For this work, we use the stellar effective temperature and luminosity to define the inner and outer boundaries of the HZ, as a function of stellar age, utilizing equations from Kopparapu et al. (2013, 2014). This method can be used substituting other HZ prescriptions, but Kopparau et al. are a commonly used point of reference. These HZ prescriptions parameterize the location of the HZ as a function of the host star luminosity and effective temperature, from which we can calculate the associated time-dependent HZ distance for each stellar evolution track. For a given orbital distance from any star we can predict how long and at what stellar age a planet would remain habitable. Thus, for a perfectly characterized star (mass, metallicity, and age known exactly), we can say with high confidence whether a planet has been continuously within the circumstellar HZ for 2 Gyr for a given HZ model.

Kopparapu et al. (2013, 2014) give several possible definitions for the HZ boundaries. The most optimistic HZ definition follows from Kopparapu et al. (2013), where they empirically determine the inner and outer HZ edge assuming that Venus and Mars once hosted habitable conditions. For the HZ edge in the RV case, they determined the effective solar flux on Venus to be 1 Gyr ago, under the assumption that there may have been liquid water on the surface prior to this time. Similarly, for the OHZ edge in the EM case, they determined the effective solar flux on Mars to be ∼3.8 Gyr ago, when liquid water likely existed on the surface.

The conservative HZ definitions follow from Kopparapu et al. (2014), where they define an IHZ edge by the “runaway greenhouse” case. Here, the effective solar flux incident on the planet becomes sufficient to completely vaporize the oceans.
given that $A$ is true, and $P(A)$ is the prior probability that the outcome $A$ is true.

We apply Equation (1) to the Tycho models and measured distributions for the stellar metallicity ($Z$) and mass ($M$) to calculate the Bayesian posterior probability. In Equation (1), $B = Z, M$ and $A = \text{CHZ}_2$, or the outcome where a given radius is in the CHZ$_2$. Equation (1) therefore becomes

$$P(\text{CHZ}_2|Z, M) = \frac{P(Z, M|\text{CHZ}_2) \times P(\text{CHZ}_2)}{P(Z, M|\text{CHZ}_2) \times P(\text{CHZ}_2) + P(Z, M) - \text{CHZ}_2 \times P(- \text{CHZ}_2)}.$$  

(2)

We now describe how we compute each component of Equation (2) for a chosen model metallicity $Z_k$ and mass $M_k$ for any given radius from the star. The index $k$ refers to the specific model used, interpolated if necessary. We calculate $P(\text{CHZ}_2)$, the initial probability that a given radius is within the CHZ$_2$, by

$$P(\text{CHZ}_2) = \sum_{i \in \text{Tycho}} \frac{(\sum_{j} t_{\text{CHZ}_2,j} \Delta Z_i) \Delta M_i}{(\sum_{j} t_{\text{CHZ}_2,j} \Delta Z_i) \Delta M_i},$$

(3)

where the index $i$ runs through the Tycho model masses $M = 0.5–1.3 M_\odot$ and the index $j$ runs through the model metallicities from $Z = 0.1–3.0 Z_\odot$. $t_{\text{CHZ}_2,j}$ is the total time the radius is in the CHZ$_2$ for a given Tycho model ($M_k, Z_k$), $t_{\text{tot},ij}$ is the total lifetime for the given Tycho model (with a maximum of 12 Gyr), $\Delta M_i = (M_{i+1} - M_i)$ is the distance between $M$ values, and $\Delta Z_i(Z_{j+1} - Z_j)$ is the distance between $Z$ values. Note that we first sum over all model metallicities and then over all model masses. The initial probability that a radius is not in the CHZ$_2$, $P(- \text{CHZ}_2)$, is given by

$$P(- \text{CHZ}_2) = 1 - P(\text{CHZ}_2).$$

(4)

The likelihood that a star has a model metallicity $Z_k$ and mass $M_k$ if a given radius is in the CHZ$_2$ is given by

$$P(Z_k, M_k|\text{CHZ}_2) = \frac{t_{\text{CHZ}_2,k} \times P(Z_k) \times P(M_k)}{\sum_{j} t_{\text{CHZ}_2,j} \times P(Z_j) \times P(M_j)},$$

(5)

where $P(Z)$ and $P(M)$ are probabilities given by the Gaussian distributions for each measured value ($Z' \pm \sigma_Z, M' \pm \sigma_M$). For example, the measured metallicity distribution is given by

$$P(Z) = \frac{1}{\sqrt{2\pi} \sigma_Z} e^{-\frac{(Z-Z')^2}{2 \sigma_Z^2}},$$

(6)

where $\Delta Z$ is defined as $Z' - Z$, the difference between the measured mean and model values. The likelihood that a star has metallicity $Z_k$ and mass $M_k$ if a given radius is not in the CHZ$_2$ is given by

$$P(Z_k, M_k| - \text{CHZ}_2) = \frac{(t_{\text{tot},k} - t_{\text{CHZ}_2,k}) \times P(Z_k) \times P(M_k)}{\sum_{j} (t_{\text{tot},j} - t_{\text{CHZ}_2,j}) \times P(Z_j) \times P(M_j)}.$$  

(7)

We combine Equations (3)–(5) and (7) to calculate the Bayesian posterior probability in Equation (2), $P(\text{CHZ}_2|Z_k, M_k)$. With a factor of $P(Z_k)$ and $P(M_k)$ canceling out, we get

$$P(\text{CHZ}_2|Z_k, M_k) = \frac{t_{\text{CHZ}_2,k} \times P(Z_k) \times P(M_k)}{\sum_{j} t_{\text{CHZ}_2,j} \times P(Z_j) \times P(M_j)},$$

(8)

This Bayesian approach to HZs aims to determine the probability that a given orbital distance from the host star has spent 2 Gyr in the HZ, following the methods of Truitt et al. (2020). Depending on the known properties of the star, this approach could follow several different cases. The simplest example would involve knowing the mass and metallicity of the star arbitrarily well, but not knowing the age. The probability in this case would depend solely on how long the orbit remains in the HZ of the star as predicted by the models. In other cases, there are one or more additional uncertainties. If the metallicity and/or mass is unknown, then all metallicity and/or mass models must be integrated over. If the metallicity or mass is known to within some uncertainty, assumed to be Gaussian, then we must weight the contribution of each model by the fit of the model mass and model metallicity to the Gaussian of each measured value. Introducing the age for the star adds an additional Gaussian prior distribution to the calculation. Here, we focus on the cases where the metallicity and mass are known to within some uncertainty, but the age is unknown, as well as the case where the metallicity, mass, and age are known to within some uncertainty. The other cases are described in detail in Truitt et al. (2020). Although this work is limited to considering metallicity, mass, and age, it can in principle be extended to include other properties, such as planetary composition and stellar activity.

### 2.4.1. Case 1: Metallicity and Mass Measurement but No Age Measurement

We first describe the case where the stellar metallicity and mass are known to within some uncertainty, but the age is unknown. In this case, the age is limited to 12 Gyr to account for the age of the universe. Our method relies on the expansion of Bayes’ theorem:

$$P(A|B) = \frac{P(B|A) \times P(A)}{P(B|A) \times P(A) + P(B|-A) \times P(-A)},$$

(1)

where $P(A|B)$ is the posterior likelihood, or the likelihood of outcome $A$ occurring given $B$, $P(B|A)$ is the likelihood of $B$
We can now calculate the Bayesian posterior probability at each radius, for a given \( Z \) and \( M \), that it is in the CHZ\( _2 \) at any time during the main-sequence lifetime, limited to 12 Gyr. Therefore, probabilities cannot exceed 10/12 because each radii from the star must be habitable for at least 2 Gyr, limiting the maximum CHZ\( _2 \) time to 10 Gyr.

2.4.2. Case 2: Metallicity, Mass, and Age Measurement

Without knowledge of the age, we previously summed the total CHZ\( _2 \) time and main-sequence lifetime. If we know the age measurement in the form of Gaussian errors, \( A \pm \sigma_A \), we can similarly use this as the probability term \( P(A) \) using the Gaussian probability

\[
P(A) = \frac{1}{\sqrt{2\pi} \sigma_A} e^{-\frac{(A'-A)^2}{2\sigma_A^2}},
\]

where \( A' \) is defined as \( A' = A \). \( P(A) \) is used to place a prior probability on the total and CHZ\( _2 \) times, \( t_{\text{tot}} \) and \( t_{\text{CHZ2}} \), thereby prioritizing model time steps closer to the mean age of the star in a similar way to how \( P(Z) \) and \( P(M) \) prioritize model metallicities and masses closer to the mean stellar metallicity and mass. \( t_{\text{tot}} \) is now given by

\[
t_{\text{tot}} = \sum_m (t_{\text{tot},m} - t_{\text{tot},m-1}) P(A),
\]

where the index \( m \) runs through each model step and \( A = t_{\text{tot},m} \). By combining Equations (10) and (8), we can now calculate the Bayesian posterior probability that each radius is currently within the CHZ\( _2 \). We apply this method to our sample of potentially habitable planets, with results summarized in Table 5 for each planet and the Bayesian posterior distributions for each star shown in Figure 4. For all nine sample stars, we applied a 4x linear and cubic interpolation to the mass models.

We use the methods for Case 1 and Case 2, as well as the 1 \( M_\odot \) HZ model from Kopparapu et al. (2014), to calculate the CHZ\( _2 \) posterior likelihood for the Sun with and without the greenhouse conservative OHZ.
temperatures, and $\sigma_T$ and $\sigma_L$ are the errors in the observations (Young et al. 2001; Pagano et al. 2015). If mass and compositional measurements are available, the search is constrained to models bracketing the measured values of mass and metallicity. Model points were averaged and weighted by their associated $\chi^2$ value. Upper and lower uncertainties were derived from the weighted standard deviation of the sample.

Uncertainties on estimates of stellar age for Sun-like stars are rarely less than 1 Gyr, oftentimes even significantly larger (Soderblom 2010; Torres et al. 2010). By operating within a Bayesian statistical framework, we can still extract useful information from a roughly constrained age. Assuming a Gaussian distribution for the best-fit age and uncertainty, we introduce the age as a prior probability distribution in the calculation. Even a poorly known age can then influence the prioritization of planets by taking into account that some planets may not have had enough time for life to produce detectable biosignatures in their atmospheres. The best-fit ages will then prove useful to determining the current habitability of the planets in these systems.

Ages for eight stars, except KIC-7340288, were available in the literature. We also generated best-fit ages for all of the stars in the sample. The ages for all nine host stars along with source references are provided in Table 3. We prefer stellar ages determined via gyrochronology for use as the age prior in Section 3 to determine the $P(CHZ_2)$ profiles for each system. Ages determined via gyrochronology tend to have tighter constraints on the age and the method is observationally calibrated, rather than relying on fits to isochrones or evolutionary tracks. For those stars with only isochrone ages, we take the average of the literature age and our fits to evolutionary tracks. For Kepler-442, which has a large upper error of $\sim 8$ Gyr, we also average the literature age with our age. Figure 2 shows an overplot of the measured literature ages and the best-fit model ages. Aside from Kepler-1455 and Kepler-441, the observed values fall within the predicted range of values determined by the models. Kepler-1455 and Kepler-441 are near the lower-mass tail of the model space ($\sim 0.5 M_\odot$) and will likely benefit from further increasing the mass and metallicity resolution and range of the model space.

Since the age determination is easily automated, we have determined ages for a sample of TESS CVZ targets from the TESS Input Catalog (TIC). The sample of 2768 stars was retrieved from the TIC version 8.1 via the Mikulski Archive for Space Telescopes at the Space Telescope Science Institute. The sample spans masses of 0.5–1.3 $M_\odot$, ecliptic latitudes of $\theta < -78^\circ$ and $\theta > 78^\circ$, and TESS apparent magnitudes $I_{mag} < 10$, and all stars have luminosities consistent with dwarf stars. Potential planets in these systems will receive the most observation time from TESS and likely from both ground- and space-based follow-up missions. Stellar ages will be essential for placing probabilistic constraints on the habitability potential of each for future target prioritization. A sample of estimated ages is included in Table 4, which includes the stellar parameters taken from the TIC.

An overview of the results of this age analysis is shown in Figure 3. Notably, we see a concentrated band of stars at higher ages and a more dispersed group of stars at lower ages. This feature is present in both the northern and southern CVZ samples, indicating no directional correlation. In addition, only one star in the sample, TIC 30270183, is known to be a member of a cluster or moving group. Hayden et al. (2015) observed two distinct populations in compositional ([$\alpha$/Fe] versus [Fe/H]) space at $R > 5$ kpc in the Milky Way’s disk. One population is roughly solar-$\alpha$ and spans a large range of [Fe/H], which merges with a lower-$\alpha$ population at supersolar [Fe/H]. This could be indicative of a lower-metallicity, older stellar population and a higher-metallicity, younger population. Determining the exact nature of these age bands is beyond the scope of this work, but we will further investigate this in the future.

### 3. CHZ$_2$ Planet Profiles

CHZ$_2$ posterior probabilities for the sample of nine potentially habitable exoplanets, as well as Venus, Earth, and Mars, are included in Table 5, with the full CHZ$_2$ distributions for each star, including the Sun, displayed in Figure 4. $<P_{0.1}>$, $<P_1>$, $<P_3>$, and $<P_{RV/EM}>$ are the posterior probabilities averaged over the orbital range of the planet for each HZ model from Section 2.3 (0.1 $M_\oplus$, 1 $M_\oplus$, 5 $M_\oplus$, and RV/EM).

Although all nine exoplanets fall within the current HZ around their host star, we determine Kepler-1455 b and Kepler-438 b to have approximately $P(CHZ_2) \approx 0$ for all cases, or essentially little to no chance of having been continuously in the HZ for 2 Gyr. This indicates that they are situated too close to the inner edge to spend a significant amount of time in the HZ and will likely soon leave the HZ.

| Stars | Age$_{gyro}$ (Gyr) | Age$_{iso}$ (Gyr) | References | Tech.$^a$ |
|-------|------------------|------------------|------------|----------|
| Kepler-1455 | 5.84$^{+1.55}_{-1.49}$ | 1.4$^{+0.6}_{-0.5}$ | 1, 2, 1, 2 |
| Kepler-438 | 6.03$^{+1.45}_{-1.45}$ | 4.4$^{+0.5}_{-0.5}$ | 2, 1, 2 |
| KIC-7340288 | 5.77$^{+0.31}_{-0.31}$ | - | - |
| Kepler-441 | 4.99$^{+0.13}_{-0.14}$ | 1.9$^{+1.5}_{-1.4}$ | 2, 1, 2 |
| Kepler-442 | 6.09$^{+1.41}_{-1.42}$ | 2.9$^{+1.6}_{-1.6}$ | 2, 1, 2 |
| HD 40307 | 4.62$^{+0.76}_{-0.76}$ | 6.9$^{+4.0}_{-4.0}$ | 3, 1 |
| Kepler-62 | 5.82$^{+0.55}_{-0.56}$ | 4.0$^{+0.6}_{-0.6}$ | 2, 1, 2 |
| Kepler-1544 | 3.50$^{+0.30}_{-0.31}$ | 3.9$^{+0.30}_{-0.30}$ | 1, 2 |
| Kepler-452 | 4.62$^{+0.36}_{-0.36}$ | 6$^{+2}_{-2}$ | 4, 2 |

Note. $^a$ Measurement Techniques: (1) Gyrochronology; (2) Isochrone.

References. (1) Torres et al. (2017); (2) Torres et al. (2015); (3) Bonfanti et al. (2016); (4) Jenkins et al. (2015).
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Figure 3. Tycho best-fit model ages for TESS northern and southern CVZ sample of F, G, K, and early-M stars, using stellar properties from the TIC version 8.

Table 4
TESS CVZ Stellar Ages

| TIC         | AgeTycho (Gyr) | M/M⊙ | Teff (K) | L/L⊙ | (M/H) |
|-------------|----------------|------|----------|------|-------|
| 55451449    | 6.62±0.99      | 1.03±0.13 | 5754±132 | 2.45±0.08 | ...   |
| 141912469   | 2.79±0.45      | 1.20±0.18 | 6232±138 | 2.68±0.12 | −0.59±0.09 |
| 38844604    | 5.67±0.29      | 1.05±0.13 | 5813±131 | 3.27±0.12 | ...   |
| 350824257   | 6.16±0.71      | 1.05±0.13 | 5830±117 | 2.76±0.10 | −0.10±0.10 |
| 233080190   | 3.05±0.51      | 1.23±0.18 | 6290±128 | 4.45±0.16 | ...   |
| 33879114    | 5.06±0.17      | 1.04±0.12 | 5782±104 | 1.26±0.05 | −0.12±0.05 |
| 280162266   | 2.85±0.05      | 1.24±0.19 | 6304±129 | 2.85±0.12 | ...   |
| 289540757   | 2.04±0.05      | 1.12±0.15 | 6034±119 | 1.22±0.04 | ...   |
| 441724181   | 5.72±0.29      | 1.06±0.13 | 5865±124 | 1.52±0.05 | ...   |
| 232629681   | 4.80±0.70      | 1.10±0.14 | 5987±108 | 4.81±0.17 | −0.04±0.03 |
| 55295030    | 6.24±0.09      | 1.11±0.14 | 6005±119 | 2.55±0.10 | −0.53±0.05 |
| 220411843   | 4.18±0.91      | 0.94±0.12 | 5398±140 | 0.58±0.02 | 0.06±0.05 |
| 219898046   | 6.41±0.35      | 1.01±0.13 | 5697±131 | 2.52±0.07 | ...   |
| 149625812   | 8.12±0.35      | 1.03±0.13 | 5751±128 | 1.87±0.07 | ...   |
| 287140180   | 5.62±0.32      | 1.04±0.12 | 5778±112 | 3.31±0.09 | ...   |
| 198161860   | 2.41±0.37      | 1.25±0.19 | 6330±127 | 2.00±0.07 | ...   |
| 441812317   | 3.52±0.27      | 1.16±0.16 | 6124±124 | 2.93±0.10 | ...   |
| 256299260   | 3.14±0.33      | 1.20±0.17 | 6219±119 | 4.33±0.18 | ...   |
| 289572073   | 4.80±0.70      | 1.12±0.14 | 6024±120 | 3.75±0.14 | ...   |

(This table is available in its entirety in machine-readable form.)

Table 5
Planetary CHZ2 Posterior Likelihoods

| Planets    | M⊕     | R⊕     | Orbit (au) | P_0 | P_1 | P_3 | P_{RV,SSA} |
|------------|--------|--------|------------|-----|-----|-----|------------|
| Kepler-1455 b | ...    | 1.75   | 0.20−0.23  | 0.0 | 0.0 | 0.0 | 0.048      |
| Kepler-438 b  | ...    | 1.12   | 0.16−0.18  | 0.001 | 0.005 | 0.007 | 0.068      |
| KIC-7340288 b | ...    | 1.51   | 0.44−0.45  | 0.900 | 0.905 | 0.905 | 0.906      |
| Kepler-441 b  | ...    | 1.462  | 0.55−0.58  | 0.345 | 0.345 | 0.34 | 0.362      |
| Kepler-442 b  | ...    | 1.34   | 0.37−0.40  | 0.340 | 0.458 | 0.584 | 0.903      |
| HD 40307 g  | 7.1    | ...    | 0.57−0.61  | 0.797 | 0.865 | 0.885 | 0.906      |
| Kepler-62 f   | ...    | 1.531  | 0.70−0.75  | 0.801 | 0.838 | 0.850 | 0.894      |
| Kepler-1544 b | ...    | 1.685  | 0.53−0.56  | 0.523 | 0.661 | 0.743 | 0.959      |
| Venus         | 0.815  | 0.950  | 0.72       | 0.0  | 0.0  | 0.0  | 0.0        |
| Earth         | 1.00   | 1.00   | 1.00       | 0.0  | 1   | 1   | 1          |
| Mars           | 0.107  | 0.531  | 1.52       | 0.402 | 0.499 | 0.533 | 0.833      |
| Kepler-452 b  | ...    | 1.511  | 1.04−1.09  | 0.402 | 0.499 | 0.533 | 0.833      |

Note: The orbital radius ranges indicated here are representative of ±1σ semimajor axis orbits and these are calculated using the periods in Table 1 and stellar masses in Table 2.

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KIC-7340288 b, an unconfirmed super-Earth planet candidate (Kunimoto et al. 2020), is consistently the highest probability target in our sample. The planet candidate’s orbital range puts it at the peak CHZ2 probability ($P \approx 0.9$) for all HZ cases considered. Given KIC-7340288 b’s relatively large size ($R = 1.511 \, R_\oplus$), the planet candidate is more likely to have retained its atmosphere and would be better able to regulate the surface temperature and retain water. Therefore, our prediction that KIC-7340288 b has remained in a stable HZ environment for 2 Gyr should be seen as a substantial indicator of the planet candidate’s potential habitability.

Notably, Earth resides at the inner edge of the CHZ2 for the 1 $M_\odot$ HZ model and is outside the inner edge for the 0.1 $M_\odot$ model. Being that Earth is the only habitable planet we know of in the universe, this shows that too conservative HZ models are likely to exclude planets that have a high potential of being habitable. Although Mars has a 100% probability of being in the CHZ2 across all models and would generally be considered...
uninhabitable, it is better to include a potential Mars-like planet rather than excluding an Earth-like planet.

4. Conclusions

This work builds upon Truitt et al. (2020) by further expanding the Tycho model space and adding a stellar age prior. The additions improve the framework’s ability to estimate the time-dependent habitability of a planet given only limited knowledge of stellar properties and planetary orbital radius. We further applied this Bayesian method to analyzing the long-term habitability of nine likely rocky exoplanets with a high probability of being in the HZ (Table 5). The posterior probability distributions used priors of measured stellar metallicity, mass, and age fitted to Tycho stellar evolution models and HZ definitions from Kopparapu et al. (2013, 2014). Two such exoplanets, Kepler-1455 b and Kepler-438 b, are shown to be unlikely to have spent 2 Gyr in the HZ for this model. KIC-7340288 b, a recently discovered super-Earth planet candidate included in our sample, is consistently found to have the highest probability of having been in the HZ for 2 Gyr.

The addition of an age prior and a method for estimating stellar ages from Tycho models will prove invaluable in future work estimating the continuous habitability of unstudied TESS candidates. By attaining fits to stellar ages comparable to published gyrochronology measurements and other isochrone ages, we demonstrate the ability to estimate ages for future potentially habitable systems with existing observations. We applied this method for age estimation to a sample of F, G, K, and early-M TESS CVZ stars from the TIC and produced ages for 2768 stars. Stars in the TESS CVZs will receive the most observing time from TESS and are the only TESS targets likely to yield detections of potentially habitable planets around Sun-like stars. The inner 5° of the TESS CVZs are also coincident with those of the JWST, so many candidates found here are the most likely for JWST follow-up. The techniques presented here can be rapidly applied to candidates detected around HabEx and LUVOIR target stars.

In the short term, we will include stellar evolution models down to 0.1 $M_{\odot}$, as this will enable the analysis of the remainder of potentially habitable systems, as well as the majority of the systems likely to be found with TESS. Increasing the resolution of the models in the lower-mass regime will provide better fits to K and M dwarfs as well.

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