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AST424 Final Report - Habitability of Circumbinary Planets

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ABSTRACT

In the last decade, NASA's Kepler and TESS missions have enabled the detection of exoplanets, revealing many worlds that differ significantly from planets in our Solar System, including more than 900 planets in multi-planetary systems. The Kepler circumbinary planets (CBPs) exist in a dynamic environment, which differs from planets orbiting single stars. This broadens our understanding of exoplanet diversity and motivates the exploration of their habitability in complex binary systems. Identifying habitable zones (HZs) in circumbinary systems is difficult because of the interplay between disrupted planetary orbits and fluctuating stellar radiation. A solution to this challenge has been proposed through the concept of Dynamically Informed Habitable Zones (DIHZs), which enable the identification of potentially habitable CBPs. In this study, we provide an overview of current approaches to calculating HZs in circumbinary systems and perform a suite of Monte Carlo experiments using empirical relationships of stellar parameters. Our result demonstrates that circumbinary systems do not necessarily preclude the possibility of habitable planets, with 4.7% of the systems tested being able to support habitable worlds. The habitability and orbital stability of CBPs depend heavily on the primary star mass, orbital period, and eccentricity of binaries. The code for this study is available at https://github.com/estherxwang/Circumbinary_HZ.

Keywords: Astrobiology, Habitable zone, Binary Stars, Exoplanets

1. INTRODUCTION

Recent advancements in detection methods have made it feasible to discover planets that are comparable in size to Earth. Over the past three decades, more than 5,300 exoplanets have been confirmed in around 3,900 planetary systems[1]. A significant number of these planets are found in binary systems (Bonavita & Desidera 2020), and some of them even orbit both stars, often referred to as circumbinary planets (CBPs hereinafter) (Doyle et al. 2011). The increasing number of detected planets in binaries provides valuable information for answering unresolved questions about such systems, including planetary formation, dynamical evolution, and the potential for harboring life (Marzari & Thebault 2019).

In comparison to the vast number of confirmed and potential circumstellar planets (i.e., planets that orbit only one of the two stars), the number of transiting CBPs discovered in the Kepler data is considerably low. To date, only 11 published CBPs have been identified so far. Detecting CBPs from available data is a challenging task due to the potential for eclipses between binary stars, which can hinder the identification of planetary transits (Windemuth et al. 2019). Since the first detection of Kepler-16b (Doyle et al. 2011), researchers have been exploring the dynamics, evolution, and formation of these CBPs.

Searching for habitable environments is one of the motivations for exoplanetary studies outside the Solar System. To search for potentially habitable exoplanets, it is crucial to have an understanding of the conditions that enable the existence of life as we know it. The concept of a habitable zone (HZ) is used to define the region around a star where Earth-like planets could have the necessary conditions to support life. The majority of habitability research has been concentrated on planetary systems that orbit a solitary star. In such systems, the planet receives a relatively steady amount of radiation on a consistent basis. Kasting et al. (1993) defines the classical HZ as the region that allows liquid water to remain on the surface of a terrestrial planet, assuming that it moves around a star in a circular orbit.

With the growing discoveries of exoplanets in binary systems, our preconceptions of what constitutes a stable, potentially habitable planetary system are being chal-

[1] http://exoplanet.eu/

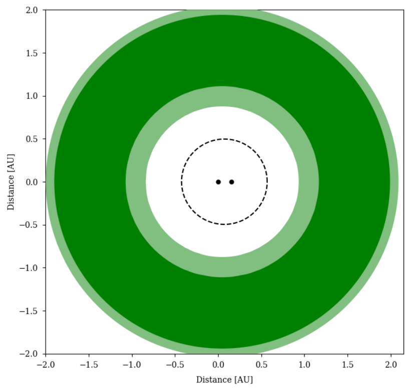

Figure 1. Example of a habitable zone of system Kepler-35 (Haghighipour & Kaltenegger 2013). The center of the figure is aligned with the center of mass of the binary star system represented by the black dots. The HZ is illustrated in two variations: the conservative HZ is denoted by dark green shading, while the extended HZ is depicted with light green shading. The dashed line shows the stability radius around the center of mass.

lenged. Calculating the habitable zones in circumbinary star systems is a complex task, as the presence of a second star introduces additional sources of radiation and gravitational effects. The amount and spectral composition of radiation reaching a potentially habitable planet vary rapidly due to the changing distance between the planet and each star, influenced by their gravitational interactions. A generalized model proposed by Haghighipour & Kaltenegger (2013) utilizes the single-star HZ prescriptions to determine HZ in binary systems. They weigh the flux received from each star based on its effective temperature and search for points where the weighted flux matches the flux received from a solar-mass star at the inner and outer boundaries. Figure 1 shows the HZ of this model using the Kepler-35 system as an example generated by an interactive website [2].

To assess the habitability of planets in binary star systems, we use the concept of Dynamically Informed Habitable Zones(DIHZs hereinafter) introduced by Eggl (2018). DIHZs are developed to incorporate the evolution of the orbital elements of planets in binary systems due to the gravitational interactions among all bodies present. It is an efficient tool that allows us to analyze the prospects for the habitability of exoplanets accounting for their orbital evolution and climate inertia.

In this study, we explore a statistical approach to investigate the possibility of habitable exoplanets in circumbinary systems. In Section 2, we outline the conditions required for the long-term habitability of CBPs and the principles of DIHZs. Using the Monte Carlo method in Section 3, we generate a large set of circumbinary systems, focusing on those with main-sequence stars, as they are the most promising for long-term habitability. We then determine the location and extent of circumbinary regions with favorable conditions for habitability in terms of both insolation and dynamical stability. In Section 4, we present our findings on circumbinary DIHZs and the dependence of binary parameters on the search for habitable planets in these systems. Finally, we draw conclusions and discuss limitations and future directions for this work in Section 5.

[2] http://astro.twam.info/hz/

2. HABITABILITY CONDITIONS

2.1. *Orbital stability*

For a CBP to be habitable, it must first be dynamically stable within its orbit. If the planet is ejected from the system, any water on its surface would eventually freeze. There exists an orbital stability limit beyond which a planet cannot have a stable orbit, which has a significant impact on the populations observed as it eliminates unstable regions of the parameter space. One can utilize numerically generated fit functions to obtain an approximate understanding of where stable and unstable systems may exist. Several derivations of the three-body stability limits were conducted prior to and after the discovery of planets in binary systems(Dvorak et al. (1989),Holman & Wiegert (1999),Mudryk & Wu (2006),Doolin & Blundell (2011)). The often-quoted empirical condition established by (Holman & Wiegert 1999) identifies critical semi-major axis values below which planetary orbits around binary stars become unstable. The critical semi-major axis in a circumbinary system is determined by the eccentricity, semi-major axis, and mass ratio of the binary, as shown in the following equation:

$$\begin{aligned}\frac{a_p}{a_b} = 1.60 + 5.10e_{\mathrm{b}} \ - 2.22e_{\mathrm{b}}^2 \ + 4.12\mu_{\mathrm{b}} \\ -4.27e_{\mathrm{b}} \ - 5.09\mu_{\mathrm{b}}^2 \ + 4.61e_{\mathrm{b}}^2 \ \mu_{\mathrm{b}}^2\end{aligned} \tag{1}$$

where a_p is the critical minimum allowable semi-major axis of a planetary orbit relative to the barycenter of the binary star's orbit, a_b and e_b represent the semi-major axis and eccentricity of the binary orbit, defined with respect to the primary star. μ represents the ratio of the mass of the secondary star to the total mass of the system ($\mu = m_B/(m_A + m_B)$). The simulations that produced these results by Holman & Wiegert (1999) assumed that the planet is mass-less and began with a circular orbit that was coplanar with the binary system. Note that for the case of $\mu = 0$, the perturber is massless such that all planetary orbits are stable, even though the equations presented imply otherwise.

Upon verification of the stability of a planet's orbit, the next step is to determine the amount of radiation it receives from the two stars. By modeling the stellar and planetary orbits and their evolution, we can estimate the exact amount and spectral composition of the radiation that reaches the planet. To achieve this, we utilize the concept of DIHZs.

2.2. *Dynamically Informed Habitable Zone*

Dynamically informed habitable zones(DIHZs) were first introduced in Eggl et al. (2012) for the study of the habitability of circumstellar planets. Later on, the methodology was applied to circumbinary planetary systems(Eggl 2018). DIHZs defines HZ for circumbinary systems with dynamical constraints using Kasting et al. (1993) model and takes both the radiative contribution of the companion star and the orbital evolution of the terrestrial planet into account. There are two DIHZs: the Permanently Habitable Zone (PHZ), and the Averaged Habitable Zone (AHZ). The Permanently Habitable Zone (PHZ) corresponds to the classical HZ, and refers to the range of orbital distances where a planet must remain to allow for the existence of liquid water near its surface, assuming the planet has low climate inertia. The criteria for a planet to reside in the PHZ is that the maximum and minimum values of insolation must not exceed habitable limits at any time. On the other hand, the Averaged Habitable Zone (AHZ) is a more relaxed definition that allows some parts of the planetary orbit to lie outside the PHZ. The AHZ takes into account the buffering effects of the planet's atmosphere and oceans, ignoring insolation extrema as long as the time-averaged insolation remains within habitable bounds. The above HZs are defined as:

$$\begin{aligned} PHZ: &\quad \max(\mathbb{S}_I) \leq 1 \quad \text{and} \quad \min(\mathbb{S}_O) \geq 1 \\ AHZ: &\quad \langle \mathbb{S}_I \rangle \leq 1 \quad \text{and} \quad \langle \mathbb{S}_O \rangle \geq 1, \end{aligned} \tag{2}$$

where

$$\mathbb{S}_{I,O}(t) = \frac{L_A}{SA_{I,O}} a^{-2}(t) + \frac{L_B}{SB_{I,O}} b^{-2}(t)$$

a and b are respectively the distance from the planet to the primary and secondary star, and I and O represent the inner and outer edges of the HZ. $\langle \mathbb{S}_I \rangle$ denotes the combined stellar insolation averaged by time. $\mathbb{S}_{I,O}(t)$ is the combined spectrally weighted insolation on the planet over time, where $SA_{I,O} = S_{I,O}(T_{eff}(A))$ and $SB_{I,O} = S_{I,O}(T_{eff}(B))$ are the spectral weights, corresponding to the limits of habitable flux for the inner and outer edges using the effective temperature of the primary and secondary star. The insolation thresholds $\mathbb{S}_{I,O}$ are parametrized as a function of T_{eff} of the star(Kopparapu et al. 2014):

$$\begin{aligned} S_I &= \mathrm{a}_I + \mathrm{b}_I T + \mathrm{c}_I T^2 + \mathrm{d}_I T^3 + \mathrm{e}_I T^4 \\ S_O &= \mathrm{a}_O + \mathrm{b}_O T + \mathrm{c}_O T^2 + \mathrm{d}_O T^3 + \mathrm{e}_O T^4 \end{aligned} \tag{3}$$

where S_I and S_O correspond to the atmospheric collapse limits of the runaway greenhouse and the maximum greenhouse respectively. $T = T_{eff} - 5780K$. The coefficients $a_{I,O}$ $e_{I,O}$ can be found in Table 1.

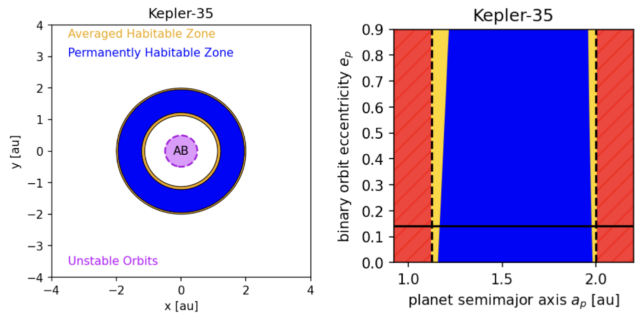

Figure 2. DIHZs of system Kepler-35. The left panel shows a top-down view of the actual system, and the right panel shows how the extent of the dynamically informed habitable zone changes with time. PHZ and AHZ are colored blue and yellow. Dynamically unstable zones (purple), and non-habitable regions (red) are also presented.

Table 1. Coefficients for the polynomial fit in Equations

	S_I	S_O	Units
a	1.107	0.356	$s_\odot$
b	1.332×10^{-4}	6.171×10^{-5}	$s_\odot K^{-1}$
c	1.580×10^{-8}	1.698×10^{-9}	$s_\odot K^{-2}$
d	-8.308×10^{-12}	-3.198×10^{-12}	$s_\odot K^{-3}$
e	1.931×10^{-15}	-5.575×10^{-16}	$s_\odot K^{-4}$

Figure 2 is a graphical representation of the DIHZ for the Kepler-35 system. On the right panel plot, it is shown how binary eccentricity changes with planet's semi-major axis. We have allowed the eccentricity of the system to vary up to much higher values from its observed value ($e_b = 0.142$) to visualize its effect on the length of HZ.

3. MONTE CARLO SAMPLE

In this section, we will simulate large(10^5) circumbinary samples and calculate the dynamically informed habitable zones using the DIHZ package [3]. Our methodology comprises generating Monte Carlo samples of binary systems by randomly sampling probability density functions of stellar masses, orbital periods, mass ratios, and orbital eccentricities following the procedure in Simonetti et al. (2020). We focus only on main-sequence stars to study long-term habitability. For each system in the sample, we compute the boundaries of the circumbinary regions where planetary orbits are dynamically stable. Finally, we evaluate the habitability of the circumbinary regions in the simulated sample based on their DIHZs.

First, we draw the mass of the primary star (m_A) of the system using the initial mass function (IMF) derived from Chabrier (2005)[4]. We draw the stellar mass from a range of $0.1 \leq \frac{m}{M_\odot} \leq 1.5$, which falls within the range of validity for the above distributions. Stars with masses greater than $1.5 M_\odot$ are excluded from consideration because their short main-sequence lifetimes compared to the evolutionary timescales for terrestrial life makes them less interesting for habitability research. Then, we draw the orbital period(P_b) of the binary system in days following the log-normal distribution suggested by Raghavan et al. (2010): $\xi(\log P_b) \propto \exp - \frac{(\log P_b - \log P_b)^2}{2\sigma^2_{\log P_b}}$ where $\log P_b = 3.69$ and $\sigma_{\log P_b} = 1.3$ for M-type primary stars, and $\log P_b = 5.03$ and $\sigma_{\log P_b} = 2.28$ for FGK-type primary stars. We use $m = 0.5$ as a threshold value between M-type stars and stars of the earlier type. In both cases, we limit our draws in the interval of $\log P$=[0.0 - 4.5]. The lower limit allows for avoiding Roche lobe overflows, while the upper limit restricts our sample to close binary systems that might host a CBP.

In the third step, we uniformly draw the mass ratio ($\mu = m_B/(m_A + m_B)$) of two stars in the system in the interval [0.2, 0.5], with the lower limit to exclude extreme parameter combinations and upper limit to ensure $m_A > m_B$. We then assign the binary orbital eccentricity (e_b) with a Gaussian distribution suggested by Stepinski & Black (2001). The distribution has the form $\xi(e_b) \propto \exp[-(e_b - \bar{e})^2/2\sigma_e^2]$ if $P_b \geq 20$ days, where $\bar{e} = 0.35$ and $\sigma_e = 0.2$. We set $P_{circ} = 20$ days. Note that this approach may lead to a bias towards lower eccentricity values.

Finally, we calculated the mass of the secondary star(m_B) using the mass ratio(μ), and the binary semimajor axis(a_b) using Kepler's Third Law. For the calculation of the DIHZs in the next step, we also added new parameters of luminosity and temperature(L_A, L_B, T_A, T_B) using stellar masses and power-law relations for stars in each sample. The parameters m_A, μ, a_b, and e_b, drawn for each binary system are then used to calculate the critical binary semi-major axis for the existence of stable planetary orbits.

[3] https://github.com/eggls6/dihz

[4] https://github.com/keflavich/imf

4. RESULT

After running the Monte Carlo simulations and collecting the sample data, we applied the methodology of DIHZs to each of the systems to calculate the inner and outer boundaries of PHZ and AHZ, respectively. The HZs divide planetary habitability into three categories: habitable, partially habitable, and uninhabitable, based on whether the critical semi-major axis of the planetary orbit lies within, partially overlaps, or is outside the inner and outer edge of the HZ. Our analysis yielded an average fraction of habitable circumbinary planets (CBPs) to be 4.7%, which is consistent with the previous work Simonetti et al. (2020), where the habitable fraction was estimated to be around $\simeq 3\% - 5\%$ for CBPs.

Additionally, we found that specific combinations of binary parameters could result in a much higher fraction of habitable CBPs. Figure 3 illustrates the dependence of habitability on the primary star mass, orbital period, and eccentricity of the binaries. In general, the distributions of the parameters under PHZ and AHZ conditions are consistent, and our findings suggest that a higher mass of the primary star, a lower orbital period, and a more circular orbit are favorable for habitable CBPs.

We must note that the habitability of circumbinary systems is significantly influenced by the eccentricity of the binaries, which affects both the dynamical orbital stability and insolation. A lower eccentricity value favors habitability in circumbinary regions. However, our approach did not consider the correlation between eccentricity and period concealed by the circularization period, which causes a decline at $e = 0$. Future studies must address this limitation.

5. CONCLUSION

Overall, our study highlights the importance of considering binary star systems when searching for potentially habitable exoplanets. The use of DIHZs simplifies the identification of HZs in these complex environments. Our Monte Carlo simulations demonstrate that a significant percentage of circumbinary systems could potentially support habitable planets, and the habitability of these planets is strongly influenced by the initial properties settings of the binary stars. For the next step, it is important to account for deviations from the idealized model we used for this study, such as neglecting the vol-

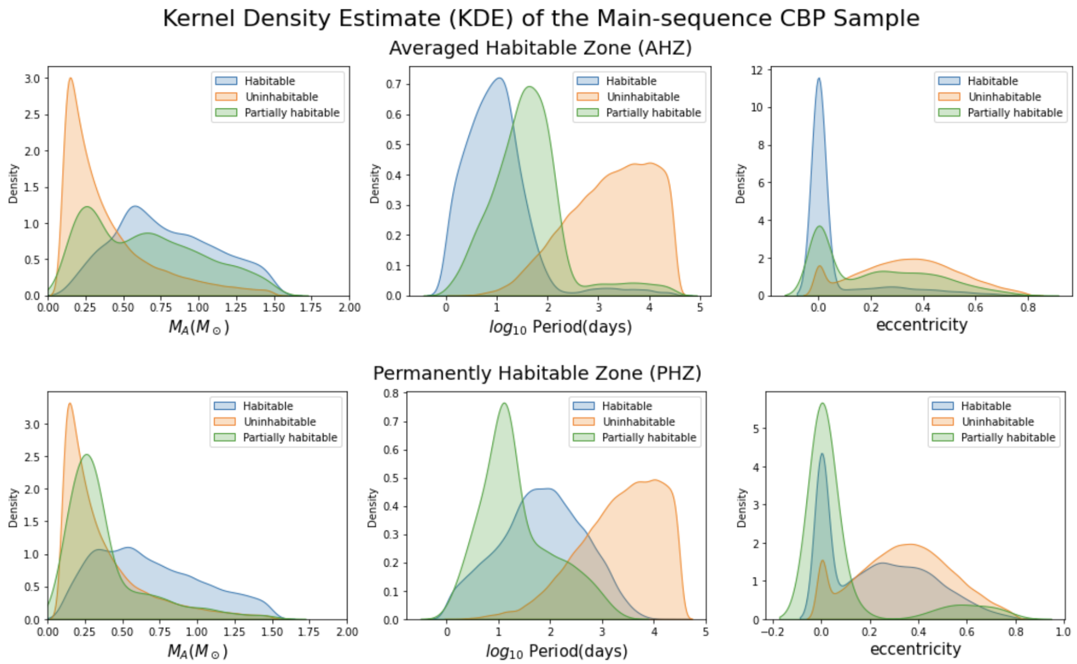

Figure 3. Kernel density estimate (KDE) of the planetary system samples under AHZ(top) and PHZ(bottom) conditions. From left to right, the figure shows the distribution of the mass of the primary star, the orbital period in the logarithm scale, and the eccentricity of the systems.

ume of the celestial bodies and the how third body with a significant mass affects the internal binary system.

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