Targeting Habitable, Terrestrial Exoplanets: An Empirical Study of Host Star Characteristics and Earth Similarity Index

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BRIEF. This study investigates the relationship between host star properties and the detection of terrestrial, potentially habitable exoplanets, emphasizing the greater likelihood of detection around M-dwarf stars.

ABSTRACT. This study utilizes the Habitable Worlds Catalog (HWC) to investigate the correlation between host star properties and the detection of potentially habitable exoplanets, with a specific focus on the conservative sample categorized by the Earth Similarity Index (ESI). Our analysis encompasses 5599 exoplanets, of which 29 are characterized as terrestrial planets having a higher likelihood of supporting liquid water. Through statistical methods, we explore how stellar parameters—including mass, luminosity, effective temperature, and metallicity—affect the detection of these exoplanets. We observe a noteworthy trend where the detection of terrestrial and potentially habitable planets appears to be more prevalent around M-dwarfs, suggesting that these cooler stars are significant targets in the search for Earth-like conditions. Furthermore, we highlight the increasing detection rates of terrestrial planets correlated with lower stellar temperatures, advocating for focused observational strategies on M-dwarfs, especially those without currently detected potentially habitable planets. This research emphasizes the necessity of refining detection methods and enhancing observational capacities for G and K stars, as their characteristics are more akin to those of our Sun, which may provide valuable insights into planetary system diversity and the environmental conditions that could support life beyond Earth.

INTRODUCTION.

Investigating the conditions of life and searching for worlds other than the earth that can host it is one of the main interests in astronomy. With recent advancements in exoplanet detection methods, and the improved technical and theoretical ability to distinguish habitable planets, this matter has become of more interest and significance than ever. As an example, the ability to gather data in a broader spectrum with James Webb Space Telescope has made the analysis of exoplanet atmospheres more accurate compared to previous instruments [1].

Many factors can be involved in determining whether a planet can harbor life or not. Nevertheless, it is generally believed that a planet is in its host system's habitable zone if it is far enough from its host star to contain liquid water [2]. In terms of other indicators of habitability, stellar magnetic field activities, planetary system dynamics, and planetary geological activities can be mentioned [3][4][5].

The Earth Similarity Index (ESI) evaluates exoplanet habitability by comparing their characteristics to Earth. Ranging from 0 to 1, higher values signify greater similarity. The ESI considers factors like planet radius, surface temperature, and density. This metric is essential in astrobiology for identifying potential extraterrestrial life targets. Nevertheless, ESI does not directly indicate the habitability of an exoplanet. Mathematically, the ESI can be calculated as

$$\mathrm{ESI} = \prod_{i=1}^{n}\left(1 - \left|\frac{x_i - x_{i0}}{x_i + x_{i0}}\right|\right)^{\frac{w_i}{n}} \qquad (1)$$

where x_i is a planetary parameter, x_{i0} is the value of the corresponding parameter for earth, and w_i is the exponent weight of the parameter. Considering only the stellar flux received by the planet, and the planet radius, this can be expressed as a distance metric using a quadratic mean [6]. According to previous studies, planets with greater ESI tend to be detected around stars with a limited range of characteristics [7].

It has long been suggested that planetary systems with similar host stars are dominated by likewise mechanics; as stated by Sir Isaac Newton in his General Scholium. Consequently, searching for habitable planets around a specific range of stars may result in a higher rate of habitable exoplanet discovery. For example, researchers at SETI institute have made efforts to refine their statistical population by attempting to differentiate the stars that are more likely to host habitable planets. They have approached this by studying several effects of the stellar criteria on the planets' habitability [8]. Consequently, the current study aims at exploring the characteristics of the discovered systems housing habitable planets and comparing them with the solar system, leading to a better understanding of the probability distribution of habitable exoplanet discoveries according to their host star.

Ultimately, it is expected that habitable and Earth-like exoplanets will be predominantly found around host stars that share characteristics similar to those of the Sun, specifically in terms of stellar mass, effective temperature, stellar metallicity, and stellar luminosity (i.e., G-type stars). Previous research indicates that lower-mass and higher metallicity stars are more likely to host a greater number of earth-like planets in their systems, increasing the probability of finding habitable or Earth-like planets around those stars [9][10][11][12].

MATERIALS AND METHODS.

This study has made use of the Habitable Worlds Catalog (HWC), which is an online database for scientists and educators about potentially habitable world discoveries. The catalog uses habitability metrics and classifications to compare exoplanets. The HWC is a project of the Planetary Habitability Laboratory at the University of Puerto Rico at Arecibo since 2011.

Exoplanet Classification.

The planets in the HWC are pre-categorized based on planet size and mass, planet equilibrium temperature, and predicted planet habitability. In terms of potential habitability, planets are classified as: I. uninhabitable, II. optimistic sample, and III. conservative sample. The definition of these terms are as follows:

I. The exoplanets that are not located in their host stars' habitable zone.

II. The exoplanets that are located in their host stars' habitable zone, but have a lower likelihood of habitable conditions due to the planets' physical characteristics.

III. The exoplanets that are more likely to be rocky planets capable of surface liquid water.

Out of 5599 exoplanets in the HWC, 29 are categorized as sample III, 41 are categorized as sample II, and the remaining planets reside in sample I.

Regarding higher ESI, the conservative sample is of more importance in this study (the average ESI for this sample is ~ 0.8). Therefore, the majority of the statistical calculations will be done specifically for this sample. The importance of sample III (more broadly earth-like) planets can be explained by the significant influence of a planet's geological and interior properties on its habitability. Therefore, planets within their host systems' habitable zone are not invariably habitable, reducing the importance of less earth-like planets in the search for extraterrestrial life. This implies that while sample II planets are located in the habitable zone, they will not be the main focus of this study.

Analysis of Host Star Parameters.

As the objective of this research is to investigate the potential correlation of the host star properties and habitable (sample III) exoplanet detection; stellar mass, luminosity, effective temperature, and metallicity were considered for analysis.

A Hertzsprung-Russell (H-R) diagram organizes the stars according to their luminosity and effective temperature. In addition, plotting an H-R diagram will indicate multiple stellar physical properties (namely age, metallicity and radius). Consequently, studying and visualizing exoplanet habitability according to the distribution of their host stars in the H-R diagram can provide a better view of the conditions of detected habitable systems. Nonetheless, stellar mass can largely affect system dynamics and the lifetime of the star, making it one of the potential determiners of exoplanet habitability and thus the discovery of potentially habitable planets.

For comparison, [8] have taken the following parameters into account to enhance their approach:

Stellar age: stars should have had sufficient time so that earth-like planets would form and evolve.

Spectral type: the aforementioned study has attempted to specifically discuss how the host stars' spectral type may affect planet habitability. Stars are classified according to the most dominant wavelength in their luminosity (which determines their effective temperature) as types O, B, A, F, G, K, and M (higher to lower effective temperature respectively).

Stellar metallicity: Regarding the potential impact of stellar metallicity on terrestrial planet formation, it can be an appropriate factor in determining whether the star is hosting habitable planets or not.

Luminosity: the most influencing parameter on a system's habitable zone boundaries is the stellar luminosity.

Statistical Analysis.

To fulfill the aims of the study, it is essential to investigate the statistical relationship between the previously stated stellar parameters, the earth similarity index, and planet habitability. This analysis will involve plotting the ESI factor of selected exoplanets against their host star parameters, such as stellar mass, effective temperature, metallicity, and luminosity, to uncover any underlying patterns. Exploratory Data Analysis (EDA) will be employed to assess the data fit and determine the distribution pattern of the systems, while descriptive statistics will summarize the characteristics of the dataset, including means, standard deviations, and ranges of both the stellar parameters and the ESI. The interpretation of these results will provide valuable insights into the empirical compliance of planet habitability and ESI with the characteristics of host stars, enhancing our understanding of the conditions that favor the detection of habitable exoplanets. Ultimately, a comparison is drawn between the conditions of habitable extrasolar systems and those present within our solar system.

RESULTS.

Figure 1 illustrates how the three samples are distributed around different types of host stars. It is apparent that the relatively fainter and cooler stars of the main sequence host sample III planets, suggesting the possibility of detecting earth-like planets is higher around K and M-type stars (93.1% of sample III planets revolve M stars with the remaining revolving K stars). Conversely, the more sun-like stars tend to host sample II planets, which can indicate that, it is presumably more difficult to detect terrestrial planets around brighter and larger stars [7].

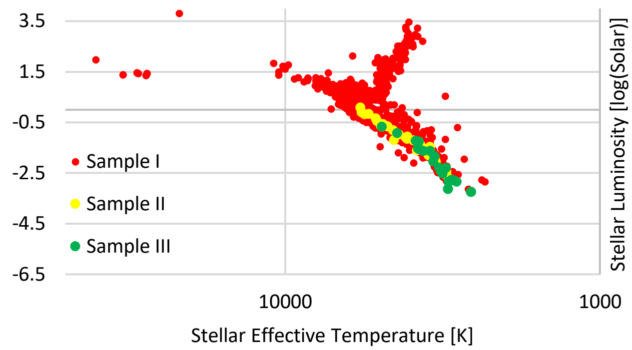

Figure 1. H-R diagram of planetary systems included in the HWC

In terms of earth similarity index, sample III planets are inevitably expected to exhibit higher values as their classification method implies. From a statistical perspective, the mean ESI for sample III is 0.7987, which is considerably more than the total average of 0.257. The corresponding standard deviation is 0.1177, with a maximum and minimum ESI of 0.968 (the highest value across the complete catalog) and 0.5757 respectively. Therefore, it can be deduced that terrestrial planets are more susceptible to detection around K and M stars relative to other main sequence stars, as a substantial proportion of them falls within sample III.

According to the data in Table 1, whilst their distribution is not remarkably concentrated in luminosity and mass, currently detected habitable planets tend to orbit substantially smaller stars than the sun. It is evident (as it was expected by analyzing Figure 1) that they are predominantly abundant around cooler stars. In addition, potentially habitable planets tend to orbit a variety of stars regarding their metallicity, with the average host star metallicity being less than the sun.

The HWC also classifies planets based on their mass and radius, identifying "terran" and "subterran" categories as suitable candidates for inclusion in Sample III, provided they reside within the habitable zone of their respective systems. A thorough examination of the distribution of terran and subterran planets could yield deeper insights into the dynamics and characteristics of these planetary systems. As illustrated in Figure 2, a notable trend emerges where M and K type stars exhibit a higher prevalence of detected terran and subterran planets. Generally, it is evident that there is an inverse relationship between the percentage

Table 1. Statistical properties of stars hosting sample III planets. Coefficient of Variation (CV) is the division of standard deviation by the mean.

Parameter	Mean	Standard Deviation	CV
Luminosity [$L_\odot$]	0.022275062	0.043807705	196.7%
Mass [$M_\odot$]	0.273793103	0.187757705	68.6%
Effective Temperature [k]	3281.016207	537.6483341	16.4%
Metallicity [Fe/H]	-0.142407407	0.175507672	123.2%

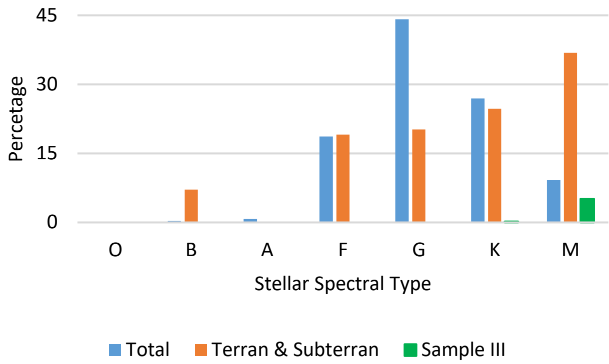

Figure 2. Distribution of planet-hosting stars across different spectral types, excluding binary stars, white dwarfs, and pulsars. The blue, orange, and green columns represent: 1. The proportion of planet-hosing stars of each spectral type relative to the total number of detected systems, 2. The ratio of stars hosting terran and subterran planets to the total number of systems of each spectral type, and 3. The proportion of sample III-hosting systems to the total systems for each spectral type.

of terran and subterran planet detection and the stellar effective temperature. In contrast, G type stars account for the majority of all detected exoplanets. This observation underscores the relative ease with which Earth-like and potentially habitable planets are discovered around M and K stars, compared to those in other spectral categories.

DISCUSSION.

The results of this study shed light on the probability of habitable and terrestrial exoplanet discovery, particularly highlighting the elevated potential for terrestrial planet detection around M-dwarfs (According to Figure 1, all detected sample III planets orbit main sequence stars, which means the only type of M stars that host them is M-dwarfs). Our analysis reveals that the bulk of currently discovered sample III exoplanets, which demonstrate a mean Earth Similarity Index (ESI) of 0.7987, predominantly orbit these cooler and fainter stars. This suggests that the likelihood of finding Earth-like planets is higher in such environments. By exploring these relationships, we not only contribute to the growing body of evidence regarding exoplanet habitability but also underscore the need for targeted observations of cooler stellar systems.

In contrary with the initial hypothesis, few G stars in the catalog host sample II planets and no sample III planets are detected around them. 9.7% of sample II planets are found around G stars, 29.3% and 61% are detected around K and M stars respectively. It is evident that both terrestrial and non-terrestrial exoplanets that lie in their systems' habitable zone are more likely to be detected around M-dwarfs. Moreover, as depicted by Figure 2, the terran and subterran planets' discovery rate increases as one moves toward lower-temperature (which also corresponds to smaller size) stars on the main sequence.

With regard to the fact that M-dwarf stars tend to have high amounts of magnetic activity (and thus stellar flares and storms) [13], it may be proposed that planets orbiting them are more exposed to high levels of UV radiation, which can compromise the potential life forms on their surface. This may prompt a reconsideration of the notion that M-dwarfs are promising candidates for the search for habitable exoplanets and extraterrestrial life. Nonetheless, recent studies have concluded that planet atmosphere might be adequately effective in protecting the potential life from harmful stellar radiation [2][3].

Whereas stellar metallicity exhibits an inverse correlation with effective temperature [14], indicating that stars with lower effective temperatures tend to be more metal-rich and potentially habitable planets are consequently predicted to be found more frequently around these metal-rich stars; as indicated in Table 1, the average stellar metallicity for sample III is lower than that of the Sun. Previous studies have highlighted that larger gas giant planets are more frequently found in metal-rich systems; however, no definitive pattern or range has been established for terrestrial planets [15][16], which does not adequately explain the observed data. A more satisfactory interpretation is provided by the significantly high coefficient of variation, which suggests that while potentially habitable planets are, on average, detected around less metal-rich host stars, they are distributed across a wide range of metallicities.

CONCLUSION.

In conclusion, our study confirms that terrestrial and potentially habitable planets are indeed more likely to be detected around M-dwarfs. This finding underscores the significance of M stars in the search for Earth-like planets, as our analysis reveals a notable concentration of exoplanet detections within the habitable zones surrounding these cooler, red stars.

Furthermore, the detection rate of terrestrial planets increases as one moves toward cooler stars, reinforcing the importance of focusing on M-dwarfs in future observational campaigns. Given that there are currently 350 M-dwarf stars without any detected potentially habitable planets in the habitable zone, yet a considerable number have either detected planets from sample II or uninhabitable terran and subterran planets (refer to Figure 2), there remains significant potential for discovery.

Future research should prioritize targeted observations of M-dwarf systems. Additionally, as G and K stars exhibit behaviors indicative of potentially habitable planets and offer larger sample sizes and a greater similarity to the Sun, enhancing the precision of measurements for exoplanets orbiting these stars will deepen our understanding of planetary system diversity and their habitability potential.

By pursuing these research avenues, we can refine our strategies in the search for Earth-like planets and expand our comprehension of planetary systems and the conditions necessary for life beyond Earth.

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