The Impact of Stellar Parameters on the Habitability of Exoplanets: A Comprehensive Review

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Exoplanet discoveries and the possibility of finding a world that can house life go up every day. As we probe the boundaries of our cosmic neighborhood, the fundamental question of habitability comes up all the time. A planet's location within the habitable zone is a crucial factor, but the time for life formation is estimated to be around 1 Gyr, and as a star evolves through its life, the habitable zone evolves as well. Thus, it is important to know that the habitable zone limits of a star are dependent on its stellar mass, metallicity, rotation, and magnetic activity. This paper summarizes the findings of Gallet & Charbonnel (2016) [1] as they do an in-depth exploration of the relationship between stellar characteristics and planetary conditions. The way they find this dependence is by using the stellar evolution model calculated with the code STAREVOL. This can be used to study the evolution of the habitable zone (HZ) and the continuously habitable zone limits (CHZLs). Using this information, they tried to estimate what can be the longest possible time for which an exoplanet will be in the star's HZ so that life can flourish.

The HZ, often referred to as the "Goldilocks Zone", is a foundational concept in astronomy that is defined as the orbital region around a star where conditions are conducive enough to support liquid water on the rocky planet's surface. The range of orbits around a star in which, at the right atmospheric pressure, the planetary surface can sustain liquid water is known as the Habitable Zone Limits (HZLs). It gives you the start and end points of the habitable zone for the star. At each instance in the evolutionary phase of a star, this paper points out the two methods used to determine the location of the HZLs. The first one is the equilibrium temperature calculation which needs a strong assumption regarding the planetary bond albedo. The total radiation that a planet reflects in relation to the total radiation that it receives from the star is known as its bond albedo. The other method includes looking at climate change as it assumes the albedo to be the ratio between the upward and the downward fluxes in the atmosphere of an exoplanet that is received and emitted by that planet. Typically the inner boundary of the HZ is determined by the runaway greenhouse limit. This occurs when a planet's temperature becomes sufficiently high, causing both the planet's surface and the lowest atmosphere to emit radiation in the near-infrared and visible wavelengths. This emission increases the outward flux while diminishing the absorption of near-IR radiation inside the planetary atmosphere. The point where the planet's surface temperature rises to almost 647 K (where the complete evaporation of water reservoirs occurs) is where this boundary ends. The outer boundary is defined by the maximum greenhouse limit, where CO_2 Rayleigh scattering decreases the greenhouse effect, fixing the planetary surface temperature at the freezing point of water. As a star evolves on the Hertzsprung-Russell diagram (HRD), its effective temperature and luminosity change, making the flux emitted by it also change. The HZLs are estimated with respect to how much flux can be received by the exoplanet.

The paper also discusses the various approaches from the literature for estimating HZLs and their impacts of HZLs. Kopparapu et al. (2014) [2] used a 1D radiative-convective, cloud-free climate model to provide an analytic expression for the effective stellar flux ($S_{\rm eff}$), which is crucial for computing HZLs. This depression is a polynomial fit based on the effective temperature of the host star, representing the strength of the greenhouse effect. The expression looks something like this [1] :

$$S_{\text{eff}} = S_{\text{eff}\odot} + aT_* + bT_*^2 + cT_*^3 + dT_*^4$$

Here, $T_* = T_{\text{eff}} - 5780K$, while $S_{\text{eff}\odot}$ shows the strength of the greenhouse effect. For the inner edge, Kopparapu et al. (2014) [2] started with a saturated "Earth" model. They increased the planet's surface temperature, examining the evolution of fluxes, planetary albedo, and the effective stellar flux until the runaway greenhouse effect is defined. For the outer edge, they simulated a planetary atmosphere with 1 bar N_2 and a surface temperature of 273 K, gradually increasing CO_2 partial pressure to find the maximum greenhouse limit, indicating the farthest distance from the star to maintain a surface temperature of 273, Kopparapu et al. (2014) [2] explored HZLs for planets of different masses and found that larger planets have wider HZLs, this work focuses on Earth-mass planets. The calculations are originally based on a Sun-like star. Still, they are applicable, through interpolation, to stars with effective temperatures between 2600 and 7200 K, corresponding to stellar masses between 0.1 and 1.4 $M_\odot$. Kopparapu et al. (2014) [2] stopped at this mass limit because stars that are greater than 1.5 $M_\odot$ have a life shorter than what we estimate life needs to evolve.

To illuminate the influences of all the factors mentioned above, a meticulous analysis is conducted in this paper using a 1 earth-mass planet orbiting a 1 $M_\odot$ star. This helps us then to know how the Earth is able to house life and what exact conditions were required for life formation. Section 4 of the paper gives us a meticulous analysis of how the HZLs change for a star from its pre-man sequence (PMS) phase to the red giant phase (RGB) phase.

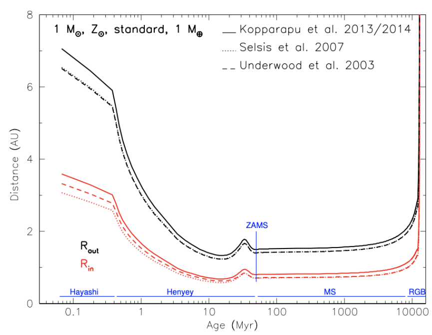

Figure 1: Evolution of the Habitable Zone Limits as a function of age for a 1 $M_\odot$ star with solar metallicity. The blue lines show the different phases of the evolution of a star. PMS (Hayashi, Henyey), ZAMS, MS, and RGB. [1]

The PMS phase initiates on the Hayashi track, characterized by a constant effective temperature and decreasing surface luminosity. During this phase, the HZLs rapidly decreased, reaching a minimum at the end of the Hayashi track. The PMS phase then continues along the Henyey track (only for stars greater than 0.5 $M_\odot$), where the star maintains nearly constant luminosity and increases in effective temperature toward the zero-age main sequence (ZAMS). At ZAMS, Figure 1 shows how the HZLs experience a slight increase and reach the local maximum. Throughout the main-sequence (MS) phase (50 Myr to 10 Gyr), the HZLs remain relatively constant. In contrast, during the RGB phase, as the star evolves towards higher luminosity and lower effective temperature, the HZLs shift outwards. The duration of these phases varies significantly, with the PMS phase being relatively short but crucial for understanding planetary habitability, especially considering early star-planet interactions. The evolving HZLs during the PMS phase may influence the surface conditions of planets and subsequently impact the potential for life development.

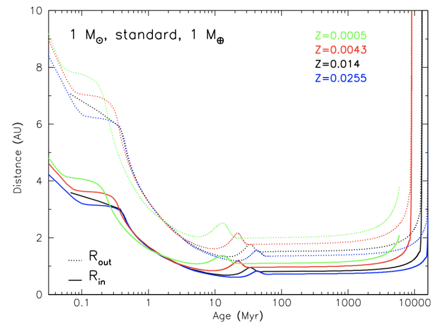

Figure 2: Evolution of the Habitable Zone as a function of the stellar age for a 1 $M_\odot$ star for varying metallicities. The inner and outer edges of the HZ are represented by solid and dashed lines respectively [1]

Metallicity significantly impacts the structure and evolution of stars, causing changes in luminosity and effective temperature along their evolutionary tracks in the HRD. Reduced metallicity decreases the opacity inside the star, facilitating the escape of energy and resulting in increased luminosity and temperature for a given initial stellar mass at a specific evolutionary phase. Consequently, the HZLs increase, approximately scaling with the square root of luminosity. Lower metallicity also shortens the overall lifetime of a star, and it shifts the inner and outer edges of the HZ outwards. This can be seen from Figure 2.

Stellar rotation is a crucial factor influencing a star's properties throughout its life, impacting its effective temperature, luminosity, and as a result, the location of the HZ. Although the evolution of stellar angular velocity is well understood, the early PMS phase and its star-disk interaction (SDI) remain mysterious. Planetary formation during the first 100 million years of a disk's lifetime may be affected by SDI, influencing the initial stages of planetary evolution. While increasing stellar rotation slightly decreases the effective temperature and luminosity, and marginally reduces the star's lifetime, the impact on HZLs is minimal, particularly after the ZAMS. The most significant effect occurs at ZAMS, where higher initial rotation rates lead to increased angular velocity during the contraction phase, affecting centrifugal effects on the HZLs. This effect diminishes with decreasing initial rotation rates, approaching standard model behavior.

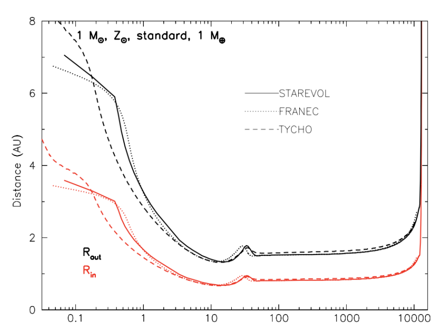

Figure 3: Evolution of the HZLs as a function of age for a 1 $M_\odot$ with solar metallicity. The inner and outer edges of the HZ are represented by the red and black lines, respectively. The solid, dotted, and dashed lines are associated with stellar models from these works. [1]

The study focuses on the impact of stellar parameters and models on the HZ evolution for an Earth-mass planet orbiting a solar-type star. First, the analysis considers numerical modeling choices, revealing a small influence of HZ prescription variations. Regarding physical stellar properties, a small change in metallicity significantly affects HZ location, particularly beyond the ZAMS and throughout the MS phase. Reduced metallicity shifts the HZ outwards due to increased luminosity and effective temperature. The rotation has a marginal impact, with the strongest effects occurring at maximum rotation during the contraction phase, resulting in a modest shift of the HZ closer to the star. Microphysics input has a minor effect, mainly influencing the PMS phase. As we can see from Figure 3, TYCHO and FRANEC codes place the HZ about 3% and 1% closer to the ZAMS compared to STAREVOL, necessitating further detailed analysis of each input's specific impact.

Increasing stellar mass shifts the HZ farther from the star, widening it in the process. During the PMS phase, HZ edges decrease continuously for low-mass stars but decrease before increasing for higher-mass stars approaching the ZAMS. HZ edges remain constant along the MS before significantly expanding during the RGB phase. The HZ shift is non-linear, with a substantial increase in the difference between HZ edges around 100-200 Myr for a 0.1 $M_\odot$ difference in stellar mass. On average, HZ width is 0.13 AU for a 0.3 $M_\odot$ star and 3.25 AU for a 2 $M_\odot$ star. Increasing mass from 1 to 2 $M_\odot$ at ZAMS shifts the HZ edges outwards by over 400%. Although higher-mass stars generally have wider HZs, the duration of the continuously habitable zone (CHZ) decreases significantly with increasing stellar mass, impacting the likelihood of complex life. The effect of changing stellar mass on temporal features mirrors that of changing metallicity, with increased mass and decreased metallicity shortening the stellar lifespan.

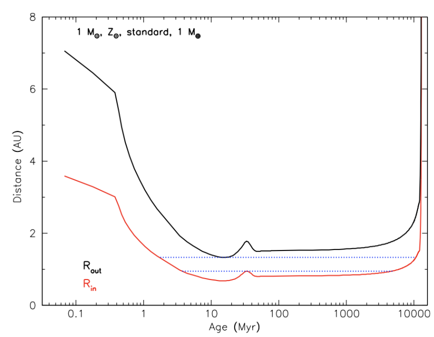

Figure 4: Continuously Habitable Zone Limits for a 1 $M_\odot$ star with solar metallicity. The inner and outer, red and black HZLs respectively, were obtained using the standard model and the Kopparapu et al. (2014) [2] prescription. The blue horizontal lines delimit the area that corresponds to the maximum duration of a given planet within the HZ.

The Continuously Habitable Zone (CHZ) is the region within the HZ where a planet, given its orbital radius, potentially stays the longest, and this is represented by the dotted blue lines in Figure 4. While conventional estimates suggest CHZ durations of 2 to 4 billion years, the paper does not impose a minimum duration in this study, focusing instead on maximizing the potential time a planet spends within the CHZ. The CHZ limits (CHZLs) for a solar-type star shift closer with increasing metallicity, and metal-rich stars have longer-lasting CHZLs due to their extended lifetimes. From Figure 4, we can also estimate that the planets closer to the outer edge of HZ stay in the CHZ for a longer period of time, but the time decreases with lower metallicity. Gallet & Charbonnel (2016) [2] also found that the CHZ width increases with decreasing metallicity. Additionally, lower metallicity stars enter the CHZ earlier. Planetary mass has a small effect on CHZLs and CHZ duration, with a slight trend toward smaller CHZLs and durations for heavier planets.

Stellar and planetary magnetic fields, generated through dynamo action in their convective layers, shape the dynamics of stars and protect planets. In stars, magnetic fields influence SDI, stellar winds, magnetic braking, and surface activity like starspots and flares. Planetary magnetic fields are crucial for shielding against solar radiation and wind. While the understanding of the paper is based on the Sun-Earth system, it's presumed that other star-exoplanet systems undergo similar magnetic interactions, emphasizing the need to understand both stellar and planetary magnetic activity for assessing habitability. Recent studies explore stellar wind interaction with planetary magnetospheres, showing potential impacts on habitability. String stellar winds, correlated with X-ray luminosity, can strip away a planet's atmosphere. Thus, considering magnetic activity, and field strength is crucial for habitability assessments.

Secular evolution induces variations in HZLs and magnetic fields. Low-mass stars (0.3 $M_\odot$) remain in a high-activity regime. Impacting habitability consistently. Solar-mass stars exhibit decreasing activity during the MS while higher-mass stars experience a high activity regime during the PMS followed by lower MS activity. While no direct correlation between stellar activity and HZLs exists, considering stellar activity is crucial for M-dwarf hosting potentially habitable planets. Analysis of the minimum planetary magnetic field needed for protection reveals insights. Earth-like planets around lower-mass stars require higher minimum magnetic fields due to higher MS activity. As stellar mass increases, MS activity decreases, leading to a reduced minimum planetary magnetic field. The evolution of the minimum planetary magnetic field is also influenced by the star's internal structure, resulting in variations during different evolutionary phases. Assessing space weather conditions, using metrics like the Rossby number, and understanding magnetic field strength emerge as critical aspects in the broader context of planetary habitability considerations.

In conclusion, assessing the habitability of class I exoplanets with liquid water surfaces requires a precise definition of the HZLs. This study highlights the importance of considering variations in HZLs as stars evolve, demonstrating their dependence on stellar mass and metallicity due to their impact on stellar luminosity and effective temperature. Stellar rotation influences tidal and magnetic torque evolution, affecting planetary orbital dynamics. A correlation between stellar activity and HZ location is identified, with the HZLs being closest to the star during periods of high stellar activity. M-dwarf stars consistently exhibit strong activity, while more massive stars display strong activity only during their early evolution. As stellar mass decreases, magnetic field strength increases during the main sequence, impacting the minimum planetary magnetic field required for effective magnetospheric protection. This poses challenges in finding habitable planets around stars other than M-dwarfs. The study provides improved constraints on HZLs using the STAREVOL stellar evolution code and aims to develop an online tool for studying exoplanet habitability. The tool will be valuable for projects such as CHEOPS, TESS, and SPIRou. Additionally, the impact of the planet's orbital motion on habitability is recognized, emphasizing the need for detailed analysis of tidal dissipation in both the planet and star, which will be incorporated into the STAREVOL code in future work.

References

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