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Astrobiologically interesting stars within 20 parsecs of the Sun

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Abstract. This project identifies and characterizes a complete sample of stars of astrobiological interest within 20 parsecs of the Sun, using data from the Hipparcos and Gaia catalogs. The main goal is the characterization of optimized targets for future orbital interferometric probes aimed at detecting biosignatures on exoplanets in the habitable zones of these stars, through the infrared spectroscopic signature of ozone, water, and methane. The selection criteria depend on multiple factors, primarily the mass, age, and chemical composition of each star, which govern the evolution rate of stellar luminosity and, consequently, the lifespan of planets within the habitable zone. Data from the literature on the stars' effective temperatures and metallicities are compiled, and their masses and luminosities are estimated based on stellar evolutionary tracks. The ages of the stars will be determined using isochronal, chromospheric, and kinematic methods. Each star's age is individually assessed in terms of the longevity of its habitable zone. A model is also developed to estimate the minimum mass a K-type star must have to prevent tidal locking from compromising the habitability of planets in its habitable zone. The result is a comprehensive catalog of F, G, and K type stars of astrobiological interest located within 20 parsecs of the Sun, all of which exhibit lifespans compatible with the emergence of photosynthetic biosignatures on potential planets within their habitable zones.

Resumo. Este projeto identifica e caracteriza uma amostra completa de estrelas de interesse astrobiológico dentro de 20 parsecs do Sol, utilizando dados dos catálogos Hipparcos e Gaia. O objetivo principal é a caracterização de alvos otimizados para futuras sondas orbitais interferométricas voltadas à detecção de bioassinaturas em exoplanetas localizados nas zonas habitáveis dessas estrelas, por meio da assinatura espectroscópica no infravermelho de ozônio, água e metano. Os critérios de seleção dependem de múltiplos fatores, principalmente a massa, a idade e a composição química de cada estrela, que governam a taxa de evolução da luminosidade estelar e, consequentemente, o tempo de permanência de planetas dentro da zona habitável. Dados da literatura sobre as temperaturas efetivas e metalicidades das estrelas são compilados, e suas massas e luminosidades são estimadas com base em trilhas evolutivas estelares. As idades das estrelas serão determinadas utilizando métodos isocronais, cromosféricos e cinemáticos. A idade de cada estrela é avaliada individualmente em termos da longevidade de sua zona habitável. Também é desenvolvido um modelo para estimar a massa mínima que uma estrela do tipo K deve possuir a fim de impedir que o travamento de maré comprometa a habitabilidade de planetas em sua zona habitável. O resultado é um catálogo abrangente de estrelas dos tipos F, G e K de interesse astrobiológico localizadas dentro de 20 parsecs do Sol, todas apresentando tempos de vida compatíveis com o surgimento de bioassinaturas fotossintéticas em potenciais planetas dentro de suas zonas habitáveis.

Keywords. Astrobiology – Stars: fundamental parameters – Methods: data analysis – Parallaxes – Stars: solar-type

1. Introduction

Life on Earth, as we know it, emerges from a finely tuned confluence of geological, atmospheric, and astrophysical conditions. As the sole known biosphere in the universe, Earth serves as our only empirical reference point in the quest to identify life beyond our Solar System. For life to originate and persist, it is not only necessary to consider a rocky planet of sufficient mass, capable of retaining internal heat and sustaining a protective magnetic field, but also one that can support long-term tectonic activity and maintain surface liquid water over gigayear timescales (Kane et al. 2021; Kasting et al 1993). However, these planetary attributes are profoundly influenced by the properties of the host star (Porto de Mello et al. 2006).

In the current era of exoplanet discovery and biosignature exploration, the critical role of the central star is often underestimated, despite its direct impact on planetary climate stability, atmospheric retention, and biological potential within the circumstellar habitable zone. The emergence and maintenance of life are intrinsically linked to a suite of stellar parameters, including mass, radius, luminosity, effective temperature, age, magnetic and radiative activity, metallicity, evolutionary status, and stellar multiplicity.

This study seeks to identify and characterize a robust sample of stars exhibiting favorable astrobiological properties, thereby establishing a prioritized target list for future missions aimed at detecting biosignatures on planets residing within their Habitable Zones (hereafter, HZs).

Furthermore, this project builds upon the foundational work conducted by (Porto de Mello et al. 2006), which identified astrobiologically promising stars within a 10-parsec radius using data from the Hipparcos catalog. The present study significantly extends this effort by doubling the search radius to 20 parsecs, thereby increasing the sample volume while maintaining a focused search for potential biosignatures. Crucially, it incorporates astrometric and photometric data from the Gaia mission, which offers superior precision relative to Hipparcos across a range of observational parameters, including parallax, proper motion, and luminosity.

The selection of candidate stars is guided by three primary astrophysical parameters. The first is stellar mass, which plays a pivotal role in determining the star's evolutionary timescale and, consequently, the stability and longevity of its circumstellar HZ (Sukoyoung et al. 2003; Kopparapu et al. 2013; Ramirez et al 2016; Kasting et al. 1993). At the higher end of the mass spectrum ($\sim 1.7\ M_{\odot}$), stars evolve more rapidly, leading to shorter-lived HZs that may not allow sufficient time for life to emerge and evolve. Conversely, at the lower mass end, particularly among K dwarfs ($\sim 0.7\ M_{\odot}$), additional complications arise, including the increased likelihood of tidal locking for planets within the HZ

(Barnes et al. 2017) and an increase in magnetic activity for lower-mass stars (at the same stellar age). This can result in synchronous rotation, leading to extreme temperature gradients between the day and night sides of the planet, as well as reduced planetary rotation rates that may hinder the development of a protective magnetic field. Tidal effects also influence atmospheric retention and long-term climate stability, making stellar mass a critical factor in evaluating astrobiological potential (Kane et al. 2021; Kasting et al. 1993; Kasting et al. 2003).

Secondly, another factor is the stellar age, which plays a critical role in allowing sufficient time for prebiotic chemistry, biological evolution, and potential atmospheric oxygenation on orbiting planets (Catling et al. 2005; Hedges et al. 2004). Third, stellar metallicity, which not only influences stellar structure and evolution but is also strongly correlated with the likelihood of forming terrestrial, rocky planets (Liu et al. 2023; Johnson et al. 2012). Together, these criteria provide a robust framework for identifying stars most likely to host planets with detectable biosignatures in their HZs.

The following sections delineates the theoretical and conceptual underpinnings guiding the selection of the astrobiologically interesting stars, hereafter termed *biostars*, with particular emphasis on the quantitative rationale behind the adopted constraints on stellar mass, age, and optimal metallicity.

2. Methods, Data and Sample

The construction of a catalog of stars with astrobiological potential follows a methodology akin to that employed by Turnbull & Tarter (2003ab), whose pioneering studies aimed to expand the list of promising targets for the SETI Institute's Project Phoenix[1]. In these studies, stars were selected based on a set of stellar physical parameters, including kinematics, multiplicity, spectral type, distance, and variability. The analysis considered all 118.218 stars from the Hipparcos catalog, and those meeting the established criteria comprised the final sample, known as the Catalog of Nearby Habitable Systems (HabCat).

The HabCat catalog was developed exclusively using data from the Hipparcos mission and included stars within a radius of up to 140 parsecs from the Sun, with the specific aim of identifying promising targets for the search for technosignatures. Technosignatures follow a conceptual framework similar to that of biosignatures but entail an additional logical assumption: they are predicated on the idea that intelligent civilizations might emit detectable signals, such as radio waves, in a sustained manner, akin to human technological activity. Thus, radio signals exhibiting characteristics or patterns that cannot be accounted for by known natural processes may be considered potential technosignatures (Lingam et al. 2021).

In contrast to the broader approach adopted by Turnbull & Tarter, the present study focuses on a smaller volume, restricting the sample to a radius of 20 parsecs. This choice prioritizes data quality over quantity, acknowledging that greater distances are often accompanied by increased uncertainties in fundamental parameters such as parallax and luminosity (Bailer et al. 2015). The ultimate goal is to identify astrobiologically relevant stellar targets to support the objectives of present and future observational missions, including the James Webb Space Telescope (JWST) and the Ariel mission (ESA), by providing a prioritized list of nearby stars whose HZs may host planets with detectable biosignatures.

3. Selection Criteria

The selection criteria for astrobiologically interesting stars encompass a range of factors that may influence the biological potential of planets located within their respective HZs. These factors pertain, for instance, to tidal interactions or to the star's own evolutionary trajectory. While such aspects were addressed in section 1, we present a quantitative discussion on the rationale behind the filters applied in the stellar selection process.

3.1. Tidal Constraints – Lower Mass Limit

As mentioned in the introduction, tidal effects on planets located within the HZ of low mass stars represent a critical factor, thereby justifying the exclusion of M-type stars as optimal candidates for habitability. In addition to these tidal constraints, the frequent flares exhibited by M dwarfs significantly enhance ultraviolet (UV) flux and contribute to atmospheric erosion on orbiting planets, both of which are detrimental to habitability (Vidotto et al. 2013; Zendejas et al. 2010; Kay et al. 2016). This decision stems from their inherently low stellar masses (ranging approximately from 0.078 $M_\odot$ to 0.57 $M_\odot$; Pecaut et al. 2013), which place the HZs extremely close to the stellar surface. Such proximity substantially increases the likelihood of tidal locking on short timescales, thereby compromising planetary rotation dynamics.

While we acknowledge that a significant fraction of the astrobiological community regards M dwarfs as legitimate targets in the search for biosignatures (Mota et al. 2025; Tarter et al. 2007; Wunder et al. 2019), the present work focuses on FGK stars in order to facilitate the interpretation of putative biosignatures, under the hypothesis that such planets experience a radiative environment broadly comparable to that of Earth, thereby enabling a more robust discussion. By excluding M dwarfs from our sample, we also avoid the confounding effects of strong stellar activity, radiative stresses, and tidal locking.

However, a similar tidal effect is observed in low-mass K dwarfs, particularly near ~0.7 $M_\odot$. In these systems, the inner edge of the HZ frequently overlaps with the region in which tidal locking occurs in less than 3 Gyr, severely undermining the long-term potential for the emergence and maintenance of a complex biosphere.

Moreover, stellar metallicity plays a critical role in this context. Metal-poor stars tend to evolve more rapidly, reaching higher luminosities over shorter timescales. As a result, their HZs migrate outward more swiftly (decreasing their lifetime), thereby mitigating tidal effects on planets situated within these evolving regions. In certain regimes of mass and metallicity, this displacement can be substantial, as evidenced in Figure 1

Stars with slightly higher masses (between 0.8 $M_\odot$ and 0.9 $M_\odot$) may still present non-negligible tidal effects, particularly in terms of rotational braking of close-in planets. The magnitude of such effects depends on multiple parameters, including stellar and planetary mass, as well as orbital distance. Notably, in specific cases, planets located at the outer edge of the HZ of stars slightly below 0.7 $M_\odot$ may escape full tidal locking.

In light of these considerations, the adoption of a minimum stellar mass threshold of 0.7 $M_\odot$ provides a pragmatic boundary for habitability analyses. This cutoff ensures that planets located within the HZ remain beyond the tidal locking region for at least 3 Gyr, a timescale commonly deemed sufficient for the emergence of life and the eventual accumulation of detectable biosignatures, about which we provide more detail below (Hedges et al. 2004; Catling et al. 2005).

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[1] Project Phoenix was an initiative led by the SETI Institute between 1995 and 2004, focused on the search for radio signals potentially emitted by extraterrestrial civilizations.

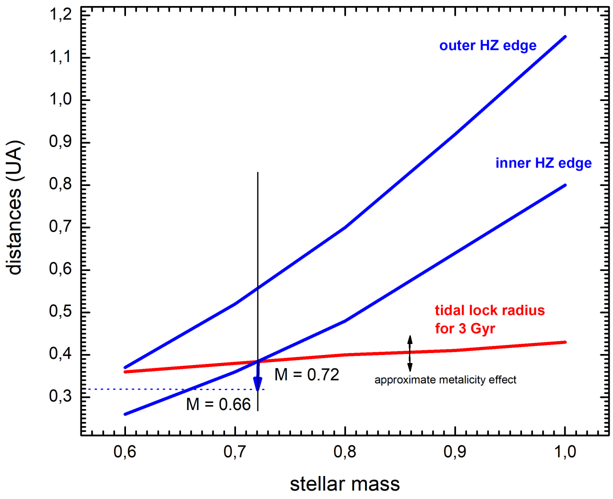

Figure 1. Orbital distance (in AU) as a function of stellar mass, showing the comparison between the tidal locking radius for 3 Gyr time elapsed (in red) and the inner and outer boundaries of the HZ (in black) for different stellar masses. Based on data from (Kasting et al. 1993; Peale et al. 1997). The double arrow shows the secondary effect of metallicity to a first approximation: metal poorer stars are more luminous at the same mass and their HZs are slightly displaced outwards, easing the effect of tidal locking, while the opposite is true for metal-richer stars.

3.2. Stellar Evolution Timescale – Upper Mass Limit

As mentioned in the introduction, stellar mass exerts a profound influence on the evolutionary timescale of a star. In this section, we quantify this influence with greater precision. Low-mass stars within the analyzed sample, particularly those discussed in the preceding subsection concerning tidal locking, do not exhibit significant limitations related to their evolutionary timescales, as their progression along the main sequence is notably slow. In contrast, as stellar mass increases, stellar evolution accelerates considerably. This shortening of stellar lifetime directly impacts the duration of the HZ, which, in some cases, may persist for less than 3 Gyr, presumably insufficient for the development and long-term maintenance of complex life.

Using stellar evolutionary models based on the isochrones from (Sukyoung et al. 2003), commonly known as the Yale–Yonsei isochrones, one can estimate the maximum residence time of a planet within the HZ.

Regarding the maximum duration of the HZ, it is determined according to the criteria established by (Kopparapu et al. 2013), where the HZ boundaries are defined based on incident bolometric flux. In this framework, the inner boundary of the HZ corresponds to 1.1 (S/S_0[2]), while the outer boundary is set at 0.37 (S/S_0). Table 1 presents the maximum residence times in the HZ for stars of various masses, along with other key temporal milestones.

The three evolutionary benchmarks (T_{hz}, T_{ms} and T_{ee}) correspond, respectively, to: (i) the moment when the inner edge of the HZ reaches the outer boundary of the ZAMS HZ, (ii) the termination of the main sequence, marked by core helium stabilization, and (iii) the point at which the inner HZ intercepts the bolometric flux equivalent to that received by Earth at ZAMS (0.736 S/S_0) corresponding to the zero-age luminosity of the early Sun, for stars with solar metallicity ([Fe/H] = 0.0).

Table 1. Ages (in Gyr) corresponding to three key evolutionary benchmarks: T_{hz} (HZ time limit), T_{ms} (Main Sequence exit), and T_{ee} (ZAMS Earth Equivalent), as explained below.

Mass ($M_\odot$)	T_{hz} (Gyr)	T_{ms} (Gyr)	T_{ee} (Gyr)
0.80	22.7	23.7	11.9
0.90	15.6	15.7	8.4
1.00	11.4	10.4	5.9
1.10	8.2	7.0	4.3
1.20	6.3	5.9	3.8
1.30	4.8	4.5	3.4
1.40	3.7	3.5	3.4
1.45	3.3	3.1	3.1
1.50	2.9	2.8	2.7
1.60	2.4	2.3	2.2
1.65	2.1	2.1	2.0
1.70	1.9	1.9	1.9

As shown, low-mass stars sustain HZ lifetimes well beyond 3 Gyr. However, from ~1.5 $M_\odot$ onward, the durations fall below this threshold, and in some cases, even drop below 2 Gyr[3]. Therefore, individualized analysis becomes necessary, particularly given that stellar metallicity significantly affects evolution and, consequently, HZ longevity. This issue will be addressed in greater detail in the following subsection. Generally, however, it is possible to define a secure upper stellar mass limit of approximately 1.7 $M_\odot$ for sustained habitability within the timescale of oxygenation and biosignature detectability.

3.3. Metallicity

As discussed in the preceding section, stellar metallicity plays a critical role in determining the rate of stellar evolution. Stars with low metallicity tend to evolve more rapidly than their metal-rich counterparts. This phenomenon arises because the opacity of a star's interior is directly influenced by its chemical composition: lower metallicity results in reduced opacity. Consequently, photons can escape more efficiently from the stellar core to the surface, leading to an increase in luminosity. As a result, hydrostatic and thermal equilibrium requires a more accelerated consumption of nuclear fuel, thereby driving a faster evolutionary trajectory.

The data presented in Table 2, which is also seen in Figure 6, clearly illustrate how the maximum duration of the HZ varies as a function of stellar mass and metallicity. For stars with masses between 1.4 $M_\odot$ and 1.5 $M_\odot$, the maximum HZ lifespan falls below 3 Gyr and, in cases of low metallicity, even below 2 Gyr. This effect is particularly pronounced for high-mass F-type stars, as is further visualized in Figure 6, derived from the isochrone models.

Given the pivotal role of metallicity in high-mass F-type stars, as well as the sensitivity of orbital distance in low-mass K-type stars (as discussed in the preceding subsection), we have compiled two lists of astrobiologically interesting stars.

The first list spans the full range of our selection criteria, encompassing stars from spectral type K7V (with $(Bp-Rp) = 1.7$ and $M(G) = 7.57$) to an upper boundary positioned between types F0V and A9V. This upper boundary is defined to include

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[2] The ratio S/S_0 represents the stellar flux received by a planet relative to the solar constant S_0 (the flux received by Earth at 1 au, ~ 1361 W m^{-2}). A value of $S/S_0 = 1$ means Earth-like insolation, $S/S_0 > 1$ indicates higher flux, and $S/S_0 < 1$ indicates lower flux.

[3] It is worth noting that 2 Gyr is often considered the lower temporal limit for the oxygenation of a planet's atmosphere—a precondition for the detection of biosignatures. While 3 Gyr remains the more conservative benchmark (see section 2), a 2 Gyr window cannot be entirely ruled out.

Table 2. Time (in Gyr) at which the inner edge of the HZ reaches the outer edge on the Zero Age Main Sequence (ZAMS) for different stellar masses and metallicities [Fe/H]: -1.0, -0.5, solar and +0.3, respectively, for columns 2 through 5.

Mass ($M_\odot$)	**-1.0**	**-0.5**	**0.0**	**+0.3**
0.80	15.8	18.5	22.7	25.3
0.90	10.6	12.8	15.6	17.7
1.00	7.4	9.0	11.4	12.9
1.10	5.4	6.7	8.2	9.3
1.20	4.3	5.2	6.3	7.0
1.30	3.3	3.9	4.8	5.3
1.40	2.6	3.0	3.7	4.1
1.45	2.3	2.7	3.3	3.6
1.50	2.0	2.4	2.9	3.2
1.60	1.7	1.9	2.4	2.6
1.65	1.5	1.8	2.1	2.3
1.70	1.4	1.6	1.9	2.1

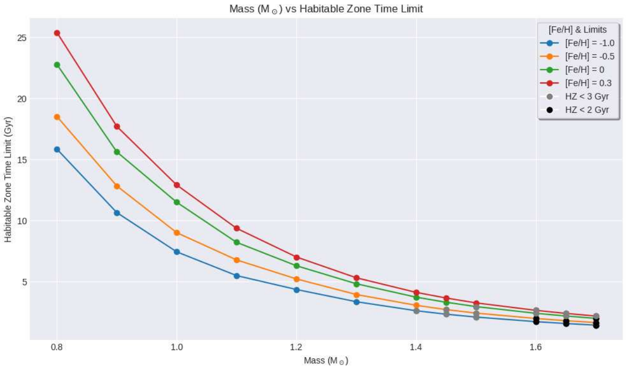

Figure 2. Graph based on the isochrone models of Sukyoung (2013), showing the maximum lifespan of the HZ as a function of stellar mass and metallicity. Regions where the HZ lifespan is less than 3 Gyr are shaded in grey; those below 2 Gyr appear in black.

stars with masses up to approximately 1.7 $M_\odot$, acknowledging that a typical F0V star has a mass of about 1.61 $M_\odot$, while an A9V star reaches roughly 1.75 $M_\odot$. Accordingly, we adopt values of $(Bp - Rp) = 0.347$ and $M(G) = 2.45$. This broad selection thus spans stellar masses from approximately 0.64 $M_\odot$ to 1.7 $M_\odot$.

The second list, a subset of the first, constitutes an optimized sample specifically designed to minimize both tidal locking effects and limitations imposed by rapid stellar evolution. In this refined set, stars are restricted to those between spectral types K5V ($(Bp - Rp) = 1.43$, $M(G) = 6.83$) and F3V ($(Bp - Rp) = 0.518$, $M(G) = 2.99$), corresponding to a narrower mass range between 0.7 $M_\odot$ and 1.45 $M_\odot$. Detailed discussions of both lists are provided in the Results section.

Beyond its direct impact on stellar evolution, metallicity also significantly influences planetary system architecture. Observational evidence suggests a positive correlation between high [Fe/H] values and the likelihood of rocky planet formation (Liu et al. 2013; Johnson et al. 2012), a prerequisite for planetary habitability. Furthermore, elevated metallicity is associated with extended durations of residence within the HZ, thereby lengthening the temporal window available for the emergence of life. Accordingly, stars with higher metallicity present more favorable conditions for habitability. Nonetheless, it is important to emphasize that metal-poor stars should not be categorically excluded, as they may still host habitable configurations under specific circumstances.

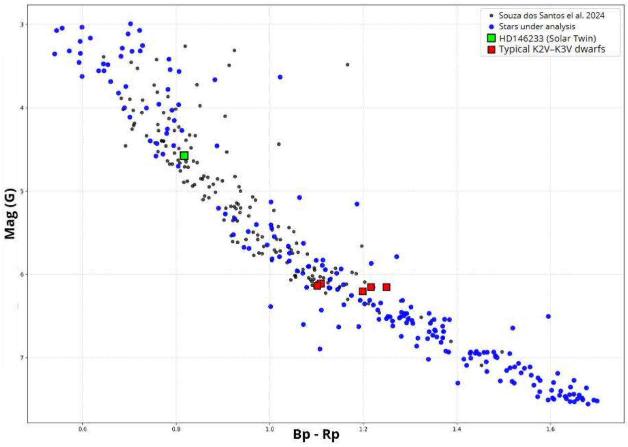

Figure 3. HR diagram with absolute magnitudes M(G) and colors Bp–Rp for all 383 astrobiologically interesting stars (“biostars”) within 20 parsecs. The gray points represent stars with well-established data in the literature, previously studied in detail by our group (Souza dos Santos et al. 2024), for which mass, age, and luminosity are already well constrained. The blue points correspond to stars currently being analyzed in the present work. Also highlighted are the solar twin HD146233 (in blue) and five representative K dwarfs (in red).

Based on these considerations, the criteria adopted for the selection of astrobiologically promising stars are as follows:

- **Stellar mass**: between 0.7 $M_\odot$ and 1.7 $M_\odot$, with upper limits assessed on a case-by-case basis.
- **Metallicity**: close to or greater than solar, ensuring the presence of heavy elements favorable to planetary formation.
- **Stellar age**: preferably greater than 3 Gyr, although values between 2 and 3 Gyr are accepted depending on the remaining duration of the HZ; the upper limit is defined by the maximum time the HZ is sustained, which varies with stellar mass and metallicity.

Based on these selection criteria, the next section presents the results concerning stars located within 20 parsecs of the Sun that satisfy the established conditions and may therefore be regarded as astrobiologically interesting.

4. Results & Conclusions

As expected from the selection criteria and the broader discussion surrounding stellar habitability, our primary list of biostars spans spectral types from F0V to K7V.

The list comprises a total of 383 stars: 63 F-type, 95 G-type, and 218 K-type dwarfs. Among these, 380 are present in the Gaia catalog, while only 3 are exclusive to Hipparcos. Additionally, 143 of the 383 stars belong to binary or multiple systems. These systems will be individually analyzed to assess the viability of biosignature detection around stars located in the HZ of such configurations, given the challenges of long-term orbital stability in binary and multiple star systems. Nevertheless, depending on stellar separation and system architecture, the emergence of life remains a plausible scenario in some of these environments.

Out of the 383 stars, only 62 have confirmed exoplanets. However, it is important to emphasize that the absence of confirmed planets does not invalidate a system, given current technological limitations and observational biases. For instance, detecting Earth-mass planets in the HZs of F- and G-type stars remains extremely challenging. A second, optimized list was derived by excluding a significant number of K dwarfs (62) and three F-type stars, yielding a refined sample of 318 biostars with potentially higher habitability prospects.

Both samples should be considered preliminary, as stellar ages have yet to be uniformly determined, either via isochronal fitting or chromospheric activity. For the subset of stars still under analysis, we are conducting spectroscopic observations of the Hα line for a large portion of the southern and equatorial targets (Souza dos Santos et al. 2024). Furthermore, we will incorporate Ca II measurements based on Mount Wilson S-index values $\langle S \rangle$ to estimate chromospheric ages across the entire sample. This is particularly challenging for K-type dwarfs, for which age determination remains notoriously difficult.

Once age estimates are finalized and stellar multiplicity fully assessed, both the main and optimized lists will be revised. Stars that fail to meet our selection criteria will be excluded, ultimately resulting in a curated list of astrobiologically interesting targets. This final catalog is intended to support future missions in the search for biosignatures around nearby stars.

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