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Astrobiologically interesting stars within 20 parsecs of the Sun

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Abstract. The template for life as we know it on Earth, based on carbon polymers and liquid water, requires specific planetary surface conditions. These conditions define the so-called habitable zone, which allows for the persistence of liquid surface water over timescales of several billion years. This definition depends on multiple factors, the main ones being the distance of the planet from its host star and the star's mass and chemical composition, which determine the rate of luminosity evolution and, therefore, the duration of a planet's residency within the habitable zone. We aim to identify and characterize a complete sample of stars with astrobiological interest within 20 parsecs of the Sun, using data from the Hipparcos and Gaia catalogs and constructing an intersection between these two datasets. The primary goal is to characterize optimized targets for future interferometric orbital probes that will attempt to detect biosignatures in exoplanets through the infrared spectroscopic signatures of ozone, water, and methane. The selection criteria include stellar mass, age, evolutionary stage, chemical composition, and chromospheric (or isochronal) age, considered favorable for the presence of rocky planets in the stellar habitable zone for a minimum of >3 billion years. We present preliminary results for the Hipparcos stellar selection (211 stars) and describe a method to use Gaia magnitudes and colors to evaluate the completeness of the Hipparcos catalog relative to Gaia. We also assess the completeness of the Gaia catalog itself relative to Hipparcos, as both catalogs are incomplete in data for apparently very bright stars and are characterized by distinct biases. There is a substantial number of stars included only in the Hipparcos catalog but not in Gaia, and vice versa. A preliminary analysis of the influence of these biases on the selection of astrobiologically interesting stars suggests that they particularly affect the population of low-mass K dwarfs.

Resumo. O gabarito de vida que conhecemos na Terra, baseado em polímeros do carbono e água líquida, exige condições superficiais planetárias específicas, definindo a chamada zona habitável, que preconiza a manutenção de água líquida superficial por escalas de tempo de vários bilhões de anos. Tal definição depende de múltiplos fatores, os principais sendo a distância do planeta à estrela hospedeira, e a massa e composição química estelar, que fixam a taxa de evolução de sua luminosidade e, portanto, o tempo de vida de seus planetas dentro da zona habitável. Visamos identificar e caracterizar, na população estelar dentro de 20 parsecs do Sol, uma amostra completa de estrelas com interesse astrobiológico utilizando os dados dos catálogos Hipparcos e Gaia e montando uma interseção entre esses dois catálogos. O principal objetivo é caracterizar alvos otimizados para futuras sondas orbitais interferométricas, as quais tentarão detectar bioassinaturas em exoplanetas pela assinatura espectroscópica no infravermelho de ozônio, água e metano. Os critérios de seleção incluem massa, idade, estágio evolutivo, composição química e idade cromosférica (ou isocronal), considerados favoráveis à presença de planetas rochosos na zona habitável estelar por, no mínimo, >3 bilhões de anos. Apresentamos resultados preliminares para a seleção estelar Hipparcos (211 estrelas) e descrevemos um método de utilizar as magnitudes e cores do Gaia para avaliar a completeza do catálogo Hipparcos frente ao Gaia. Avaliamos também a completeza do próprio catálogo Gaia, frente ao Hipparcos, já que ambos os catálogos são incompletos nos dados para estrelas de brilho aparente alto, e são caracterizados por vieses distintos. Há número substancial de estrelas contidas apenas no catálogo Hipparcos mas não no Gaia, e vice-versa: uma análise preliminar da influência destes vieses na seleção das estrelas astrobiologicamente interessantes sugere que elas afetam especialmente a população de anãs K de massa baixa.

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

1. Introduction

The blueprint of life as we know it on Earth, based on carbon polymers and liquid water, requires specific planetary surface conditions, defining the so-called habitable zone, which dictates the maintenance of surface liquid water over time scales of several billion years. This definition depends on multiple factors, the main ones being the planet's distance from the host star, and the star's mass and chemical composition, which determine the rate of evolution of its luminosity and, consequently, the lifespan of its planets within the habitable zone. (Porto de Mello et al. 2006).

We aim to identify and characterize a complete sample of stars with astrobiological interest within 20 parsecs of the Sun, using data from the Hipparcos and Gaia catalogs and creating a composition and an intersection between these two catalogs. The main objective is to characterize optimized targets for future interferometric orbital probes, which will attempt to detect biosignatures in exoplanets through the infrared spectroscopic signature of ozone, water, and methane. The selection criteria include mass, age, evolutionary stage, chemical composition, and chromospheric (or isochronal) age, considered favorable for the presence of rocky planets in the stellar habitable zone for at least >3 billion years.

2. Metodology

The creation of this sample of astrobiologically interesting stars continues the work presented in the group's previous study (Porto de Mello et al. 2006), which focused on identifying such stars within 10 parsecs of the Sun. The concept aligns closely with the *Catalog of Nearby Habitable Systems* (HabCat) by Turnbull et al. (2003a). HabCat was derived from the Hipparcos Catalogue, analyzing data on distances, stellar variability, multiplicity, kinematics, and spectral classification for its 118218 stars.

While Turnbull's catalog encompasses a broader range of stars within 140 parsecs of the Sun, our sample targets a smaller yet more detailed subset by combining data from both the

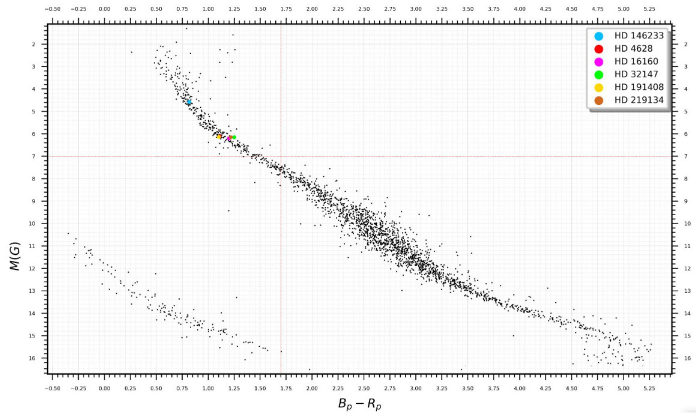

Figure 1. HR diagram constructed using Gaia's $M(G)$ magnitudes and $BP - RP$ color indices for stars located within 20 parsecs of the Sun.

Hipparcos and Gaia catalogues. By cross-matching these two catalogues, we constructed HR diagrams for the resulting sample. This approach allows us to analyze and identify the specific types of stars we aim to study, focusing primarily on FGK stars.

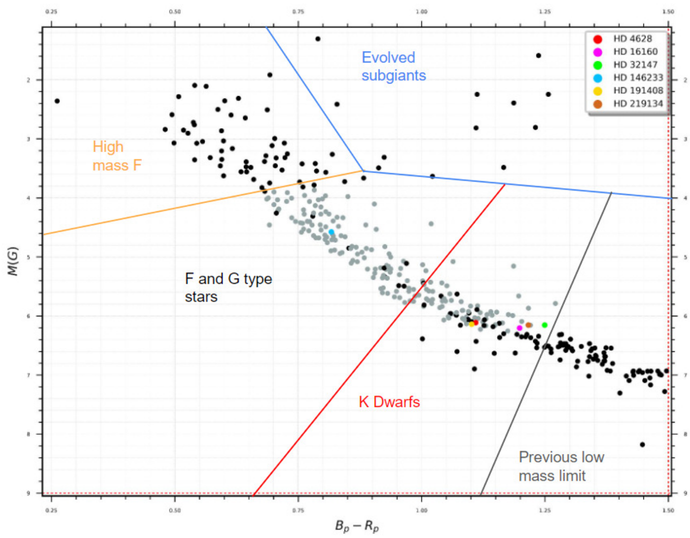

Figure 2. Zoomed-in view of the upper-left region of Fig. 1, constructed using Gaia's $M(G)$ magnitudes and $BP - RP$ color indices for stars within 20 parsecs of the Sun.

3. Results

Using Gaia's $M(G)$ magnitudes and $BP-RP$ color indices, we constructed this first diagram, displaying an HR diagram of all stars observed by Gaia. Distinct stellar populations are evident, such as white dwarfs in the lower-left, M dwarfs along the main sequence, and even brown dwarfs in the lower-right region. Most of these stars will not be included in the final sample, as we are specifically targeting FGK-type stars with masses similar to the Sun (ranging from around 0.7 to 1.3 $M_{\odot}$) and ages exceeding 3 Gyr.

The blue star represents 18 Scorpii, a solar twin used to symbolize the Sun in this diagram. The other colored stars correspond to K-type stars, which were used to define the lower boundary of the sample from the group's 2006 study (Porto de Mello et al. 2006). This boundary will be slightly extended, as updated tidal models suggest that planets in the habitable zones of some K dwarfs may remain "free" from tidal locking issues. A closer look in the upper left of the graphic is seen in Fig. 2.

In Fig. 2, we present a more detailed view of the upper-left region of Fig. 1. Here, we can observe additional stellar populations, such as evolved subgiants in the upper-right and upper-left regions, both of which will not be included in the final sample. In the central region, we see F-type and G-type stars, including 18 Scorpii, while the lower portion features K dwarfs, marked by the previously discussed lower boundary of the 2006 sample.

The gray stars represent the 211 stars, also cataloged in Hipparcos, that have already been selected for the final sample and are referred to as "biostars." The black stars in the lower region correspond to stars that were "missed" by Hipparcos, including many K dwarfs and a few F-type and G-type stars.

It is important to note that the presence of other stars in the diagram does not preclude their inclusion in the final sample, as we are still analyzing them. Furthermore, we plan to extend the previous lower boundary to incorporate more K dwarfs into the selection.

The selection is still in progress, but we already have observations of the Hα spectral range for the southern/equatorial stars of our sample (dos Santos et al 2024). Additionally, we will use Ca II measurements from Mount Wilson <S> indexes to characterize the chromospheric ages of all stars in this sample. This is particularly challenging for K dwarfs, for which constraining ages is difficult. From this sample, we will select stars older than 2–3 billion years to ensure sufficient time for planets to develop biosignatures. This estimate is based on Earth's history, where atmospheric oxygenation took approximately 2 billion years (Catling et al. 2005).

We are also calculating tidal models to determine the minimum stellar mass required to ensure that the habitable zone is free from tidal issues, such as planets becoming tidally locked or having excessively slow rotation periods. In K-type stars, tidal forces become problematic because the habitable zone is much closer to the star, causing the planet's rotation to slow more rapidly than what we observe with the Sun and Earth. When a planet's rotation period extends to several days, its climate may start to become extreme due to excessive insolation on the day side, resulting in extremely high temperature variations.

4. Conclusions

There is still considerable work to be done on the sample itself, particularly in building more diagrams and gathering more data from the Hα regions for all the stars. Additionally, we will compare the Gaia and Hipparcos catalogs with other catalogs, such as the *Bright Star Catalogue* (Hoffleit et al. 1991), which, as its name implies, focuses on bright stars. These are often underrepresented in Gaia and Hipparcos due to completeness issues. By cross-referencing these catalogs, we aim to minimize the likelihood of "missing" stars, resulting in a more comprehensive and robust sample.

The primary focus—and challenge—of this study lies in K-type stars. These stars present two significant difficulties: first, accurately determining their ages is more complex compared to F and G stars; second, estimating the minimum stellar mass necessary to prevent problematic tidal interactions in their habitable zones is equally challenging. These issues are interconnected: if the star is very old, even a planet that began with rapid rotation will likely experience significant deceleration over time due to tidal forces. For instance, studies suggest that when Earth formed, its rotation period was approximately 10–15 hours (though this estimate carries uncertainties). Over billions of years, Earth's rotation has slowed to its current 24-hour period.

The goal of this reduced sample, constrained within a 20-parsec limit, is to achieve comprehensive characterization of the stars, including effective temperature, chemical composition, evolutionary stage, and, most importantly, age. This detailed information will enable us to estimate the potential lifespan of exoplanets in the habitable zones of these stars. Our efforts will include utilizing various chromospheric indicators for age determination, a particularly valuable approach for the population of K-type dwarfs.

Once the sample is finalized, even if not all systems host confirmed exoplanets, it will serve as an excellent set of targets for future missions dedicated to the search for biosignatures.

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