

Where in the Milky Way do exoplanets preferentially form?

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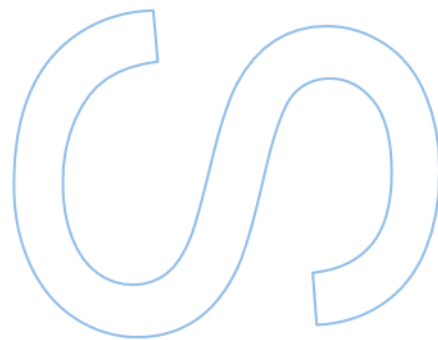
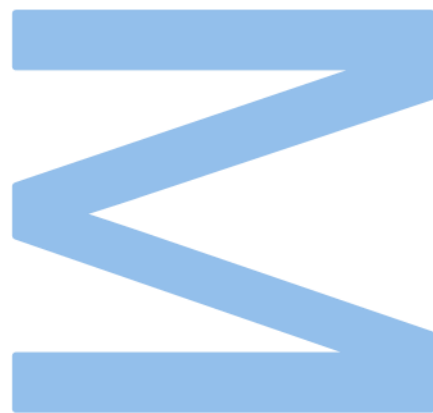
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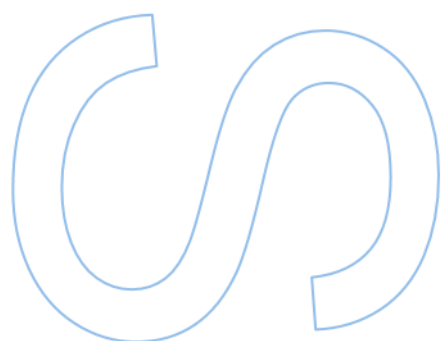
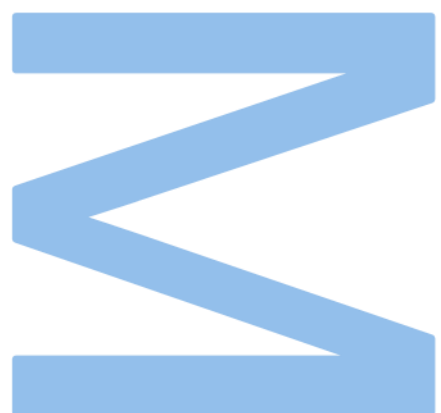
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Abstract

Over 5000 exoplanets have been discovered thus far, implying that planet formation is a universal process that occurs around the majority of stars in the solar neighbourhood. The discovered exoplanets exhibit a large diversity of properties, and some are expected to be related to the environment of their host stars, which in turn is dependent on the location and time of their formation in the Galaxy.

The timing of star-planet formation is reasonably simple to establish because stellar ages can be measured using a variety of techniques. However, stars move away from their birth location and travel around the Galaxy during their lifetimes. Nonetheless, by considering stellar ages and chemical composition, it is possible to infer their birthplaces. This is because the chemical composition of the Galaxy varies through time as a function of the galactocentric radius, meaning that each given locus of the Galaxy at any epoch has a unique chemical makeup.

The aim of this dissertation is to infer the Galactic birthplaces of stars and, consequently, their planets, with the ultimate goal of studying the Galactic aspects of exoplanet formation. For that, two samples of stars hosting planets (SWEET-Cat and CKS) and a sample of stars without any detected planets (HARPS) were taken from the spectroscopic catalogues SWEET-Cat (Santos et al. 2013), CKS (Petigura et al. 2017) and HARPS-GTO (Delgado Mena et al. 2017), respectively. The photometric data were acquired from the *Gaia* DR3 (Gaia Collaboration et al. 2022) and 2MASS (Skrutskie et al. 2006) catalogues. The astrometric data were taken from the *Gaia* DR3. From these parameters, the first step was to derive stellar luminosities. For that, the reddening caused by interstellar dust was computed with STILISM, and the bolometric corrections on magnitudes were done with YBC. In the following step, stellar ages were estimated with PARAM, an isochrone-fitting tool with Bayesian methods. Finally, the Galactic birthplaces of exoplanets were inferred following the work of Minchev et al. 2018, which consisted of projecting stars back to their birth positions based on their estimated age and metallicity.

The distributions of metallicity, age, and Galactic birth radius of stars hosting planets were studied and compared to their non-host counterparts. It was found that, on average, stars hosting planets are younger, have higher metallicity, and form at smaller Galactic radii compared to stars without planets. The formation efficiency, calculated as the relative frequency of exoplanets, appears to decrease with the Galactic radius, for which this dependence seems to be stronger for high-mass planets than for low-mass planets.

In particular, the formation efficiency of high-mass planets at early times is lower and more concentrated towards small galactocentric radii. Over time, the formation efficiency of these planets increases steeply, encompassing larger galactocentric radii. These results are in agreement with (i) the observed ISM negative metallicity gradient, where at small galactocentric radii, the metallicity is higher, favouring the formation of these planets, as predicted by core accretion models; (ii) the flattening of the ISM metallicity gradient with time, favouring the formation of these planets at larger galactocentric radii; (iii) the ISM enrichment with time, which favours the formation of these planets around younger stars. The formation efficiency of low-mass planets seems to not be dependent on time but has a subtle dependence on galactocentric radius, appearing to be higher at small galactocentric radii as high-mass planets. Non-host stars form less over time, as the ISM enriches and form preferentially at larger galactocentric radii, where the metallicity is lower.

Resumo

Atualmente mais de 5000 exoplanetas foram detetados, o que sugere que a formação de planetas é um processo universal que ocorre em torno da maioria das estrelas localizadas na vizinhança solar. Os exoplanetas detetados mostram uma grande variedade de propriedades, pelo que se espera que algumas destas propriedades estejam relacionadas com o ambiente no qual as suas estrelas se formam. Por sua vez, este depende do local e do tempo em que as estrelas se formaram na Galáxia.

A determinação do momento de formação estrela-planeta é razoavelmente simples de estabelecer, dado que as idades das estrelas podem ser estimadas por diversos métodos. Todavia, ao longo das suas vidas, as estrelas afastam-se do local onde se formaram e movem-se pela Galáxia. Tendo em conta que a composição química da Galáxia varia ao longo do tempo em função do raio galactocêntrico, cada local da Galáxia tem, num determinado momento, uma composição química única. Assim, considerando a idade e a composição química das estrelas, é possível inferir os locais de nascimento das estrelas no disco Galáctico.

O principal objetivo desta dissertação é inferir os locais de nascimento das estrelas e, consequentemente, dos seus planetas na Via Láctea, com o objetivo final de estudar os aspetos galácticos da formação dos exoplanetas.

Duas amostras de estrelas que albergam planetas e uma amostra de estrelas sem planetas detetados foram retiradas dos catálogos espectroscópicos SWEET-Cat (Santos et al. 2013), CKS (Petigura et al. 2017) e HARPS-GTO (Delgado Mena et al. 2017), respectivamente. Os seus parâmetros fotométricos foram recolhidos dos catálogos *Gaia* DR3 (Gaia Collaboration et al. 2022) e 2MASS (Skrutskie et al. 2006), enquanto que os dados astrométricos foram recolhidos apenas do catálogo *Gaia* DR3. Com estes parâmetros, o primeiro passo foi estimar a luminosidade das estrelas. O avermelhamento causado pela poeira interestelar foi determinado através do STILISM. A correção bolométrica foi calculada através do YBC. O seguinte passo foi estimar as idades estelares por ajustes de isócronas com métodos Bayesianos (PARAM), tendo em conta a metalicidade, temperatura efetiva e composição química das estrelas. Por último, os locais de nascimento das estrelas foram inferidos, seguindo o método desenvolvido por Minchev et al. 2018, que consiste na projeção das estrelas de volta para a sua posição de origem no disco galáctico, tendo em conta apenas as idades estimadas e as suas metalicidades.

As distribuições das metalicidades, idades e locais de nascimento galácticos das estrelas que

albergam planetas foram estudadas e comparadas com estrelas sem planetas detetados. Observou-se que, em média, as estrelas que albergam planetas são mais jovens, têm uma metalicidade maior e formam-se a raios galactocêntricos menores em comparação com estrelas sem planetas detetados.

Em geral, a eficiência de formação de estrelas com planetas diminui com o raio galactocêntrico. No entanto, essa dependência é mais forte para estrelas com planetas massivos do que para estrelas com planetas menos massivos. Em particular, a eficiência de formação de planetas massivos nos tempos iniciais após a formação da Galáxia é menor e mais concentrada para raios galactocêntricos menores. Ao longo do tempo, a eficiência de formação destes planetas aumenta rapidamente, abrangendo raios galactocêntricos maiores. Estes resultados estão de acordo com (i) o observado gradiente negativo radial da metalicidade na Galáxia, pelo que a metalicidade é mais elevada em direção do centro da Galáxia, favorecendo a formação destes planetas, como previsto pelo modelo de acreção; (ii) o atenuamento do gradiente de metalicidade ao longo do tempo, favorecendo a formação de planetas a cada vez raios galactocêntricos maiores; (iii) o enriquecimento do meio interestelar ao longo do tempo, favorecendo a formação destes planetas ao redor de estrelas cada vez mais jovens. Já a eficiência de formação de planetas de baixa massa é independente do tempo, mas dependente, embora ligeiramente, da distância ao centro da Galáxia. Estrelas sem planetas detetados formam-se cada vez menos ao longo do tempo à medida que o meio interestelar enriquece, e preferencialmente a raios galactocêntricos maiores, onde a metalicidade do meio interestelar é menor.

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Acronyms

RV	radial velocity	MS	main sequence
CKS	California-Kepler Survey	pp	proton-proton
HARPS	High Accuracy Radial velocity Planet Searcher	CNO	carborn-nitrogen-oxygen
ESPRESSO	Echelle SPectrograph for Rocky Exoplanets and Stable Spectroscopic Observations	SG	subgiant phase
VLT	Very Large Telescope	RGB	red-giant branch
TESS	Transiting Exoplanet Survey Satellite	PDF	probability density function
PLATO	PLANetary Transits and Oscillation of stars	CI	confidence interval
ESA	European Space Agency	GMCs	giant molecular clouds
ISM	Interstellar Medium	SN	supernova
CA	core accretion	KDE	kernel density estimation
GI	gravitational instability	KS test	Kolmogorov–Smirnov test
SNR	signal-to-noise ratio	LMPHs	low-mass planets hosts
HRD	Hertzsprung-Russell Diagram	LMPs	low-mass planets
		HMPHs	high-mass planets hosts
		HMPs	high-mass planets
		ELMPHs	exclusively low-mass planets hosts

Chapter 1

Introduction

In the last decades, thanks to advancements in technology, a variety of techniques for detection and characterization of planets outside the Solar system - known as extrasolar planets or exoplanets - have been successfully developed by astronomers. Earlier in 1992, the first exoplanets were detected around a pulsar by Wolszczan and Frail [1992](#) with radio telescopes. A few years later, the first exoplanet orbiting a solar-type star was detected through high-precision radial velocity measurements by Mayor and Queloz [1995](#). Since then, there has been enormous progress in the discovery of exoplanets, and over 5000 have been detected and confirmed.

Figure 1.1 presents a diagram of the confirmed exoplanets in the NASA Exoplanet Archive¹ (Akeson et al. [2013](#)) based on their detection methods. It is evident that the first discoveries were affected by a bias in observation, making it easier to detect massive planets. Nevertheless, with the improved accuracy of instruments, an increasing number of low-mass exoplanets have been detected over the years. As of today, radial velocity (RV) and transit methods are the most successful ones, being responsible for the discovery of 1048 and 4103 exoplanets, respectively. Following them are the microlensing method with 201 exoplanets discovered and direct imaging with 68 exoplanets. The least successful method is astrometry, with only 2 exoplanets discovered. *Gaia* mission is expected to detect thousands of planets with the astrometry method at the end of the nominal mission (Perryman et al. [2014](#)).

Some details about these methods are provided in the next Section.

1.1 Detection Methods of Exoplanets

1.1.1 Radial Velocity

The radial velocity method was first proposed by Struve [1952](#). This technique is based on the gravitational pull exerted by an orbiting planet on its host star. This produces small variations

¹<https://exoplanetarchive.ipac.caltech.edu/>

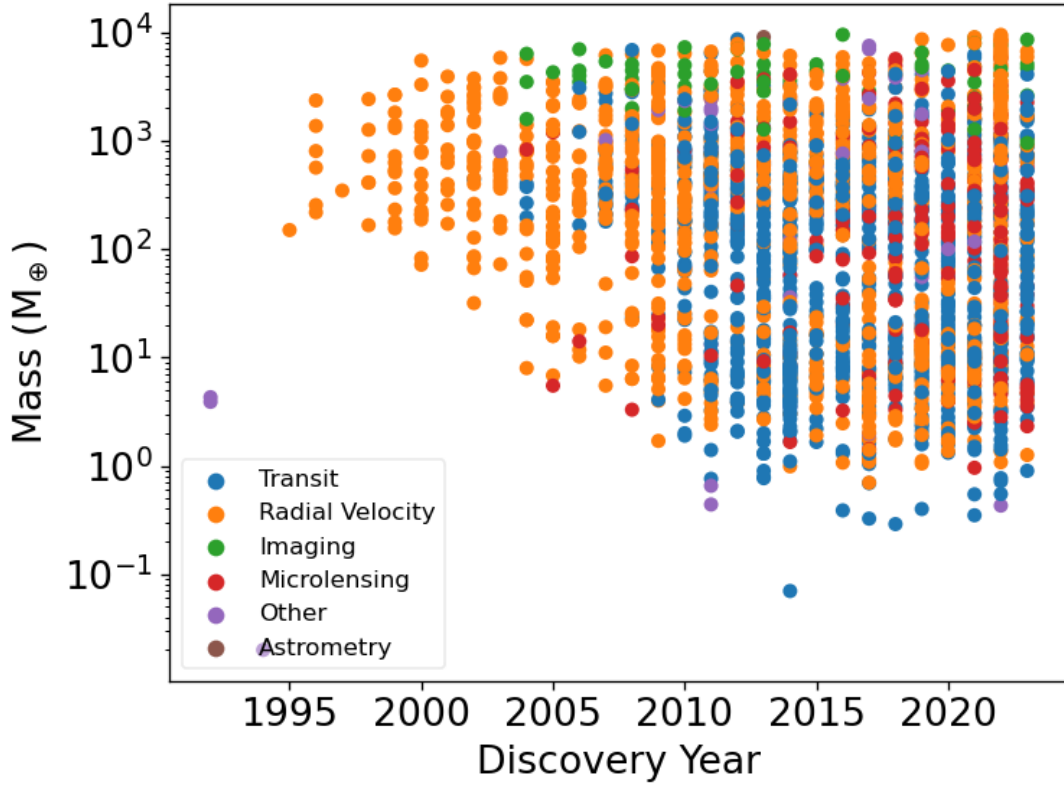


Figure 1.1: Mass of known planets as a function of discovery year. The detection methods are shown using different colors. Data taken from NASA Exoplanet Archive as of 04/08/2023.

in the radial velocity (i.e., velocity along the line of sight of an observer) of the star around the centre of mass of the star-planet system.

The changes in RV of the star are measured from Doppler shift of the light received from the star. If the star moves towards the observer its light is blueshifted, whereas when the star moves away, its light is redshifted. This is illustrated in figure 1.2a. The RV variations can be measured from the displacement of the spectral lines using the Doppler equation in the non-relativistic case,

$$\frac{\Delta\lambda}{\lambda} = \frac{v_r}{c}, \quad (1.1)$$

where $\Delta\lambda$ is the wavelength shift observed, λ is the reference wavelength, v_r is the RV and c is the speed of light.

By obtaining the spectrum of the star over an extended period of time, the periodic signal in the RV measurements (figure 1.2b), caused by the presence of a planet, can be interpreted using the Keplerian function (Murray and Correia 2010):

$$v_r(t) = K[e \cos(\omega) + \cos(\omega + f)] + V_Z, \quad (1.2)$$

where V_Z is the systemic velocity, ω is the longitude of periastron and f is the true anomaly. K is the semi-amplitude of the RV signal and depends on the mass ratio between the star $M_\star$ and

the planet M_p , the orbital inclination i , the orbital period P , and the eccentricity of the orbit e (Cumming et al. 1999),

$$K = \left(\frac{2\pi G}{P} \right)^{1/3} \frac{M_p \sin(i)}{(M_p + M_\star)^{2/3}} \frac{1}{\sqrt{1 - e^2}}, \quad (1.3)$$

where G is the gravitational constant. These parameters can be calculated by fitting the RV signal through time to the Keplerian function. The inclination of the orbit, however, remains unknown because the method only detects changes in the motion of the star in the line-of-sight of the observer. Consequently, the mass of the planet also remains uncertain by the unknown factor $\sin(i)$, and only the minimum mass, $M_p \sin(i)$, can be derived. On average, the masses are underestimated by ~ 0.79 (Lovis and Fischer 2010).

The RV technique is biased towards low period, and thus close-in planets, $P^2 \propto a^3$, or high-mass planets, since they produce a higher amplitude signal on the star's RV. Therefore, high precision is required to detect the RV amplitude signal produced by low-mass and outer planets. Precise RV instruments have been developed in recent years. The High Accuracy Radial velocity Planet Searcher (HARPS) at the ESO La Silla 3.6 m telescope was designed to reach accuracies of 1 m/s, enabling the detection of close-in super-Earths and Neptune-mass planets (Mayor et al. 2003). The Echelle SPECTROGRAPH for Rocky Exoplanets and Stable Spectroscopic Observations (ESPRESSO), mounted at the Very Large Telescope (VLT), is built to reach an ultimate RV precision of 10 cm/s, which is necessary to detect Earth-like planets (Pepe et al. 2014).

Stellar activity also may induce RV amplitude signals high enough that might be indistinguishable from those produced by planets.

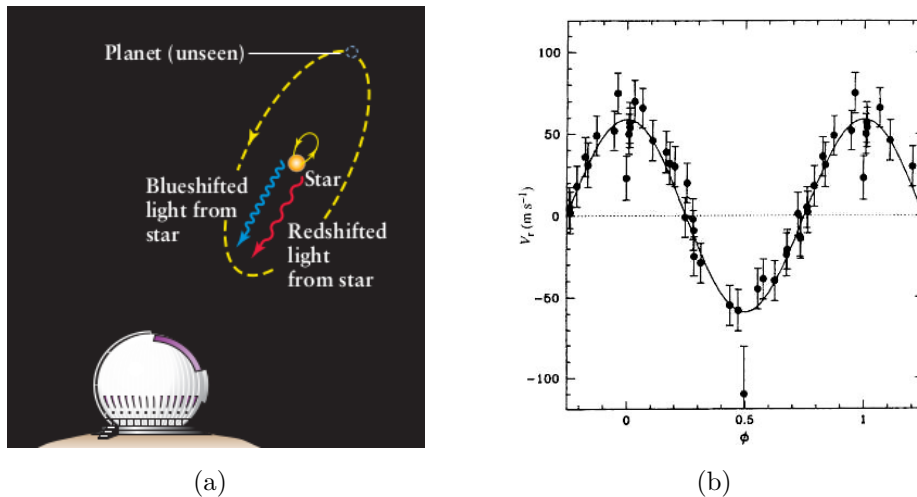


Figure 1.2: (a) Illustration of the RV method from Freedman and Kaufmann 2005. (b) RV curve of 51 Pegasi b from Mayor and Queloz 1995.

1.1.2 Transit

The transit method for exoplanet detection was first proposed by Rosenblatt 1971. Years later, the first transiting exoplanet, HD 209458 b, was observed by Charbonneau et al. 2000. A transit occurs when a planet passes in the line-of-sight between its host star and an observer. The planet blocks some light received from the star, causing a decrease in the observed stellar flux F , over a short period of time. This is seen in figure 1.3 as a dip in the observed light curve of the star. Knowing the fractional change in the stellar flux - the transit depth, ΔF - the size of the planet can be inferred if the size of the star is known. From Seager and Mallén-Ornelas 2003, the transit depth is proportional to the square of the ratio between the planet's radius, R_p , and the star's radius, $R_\star$,

$$\Delta F \propto \left(\frac{R_p}{R_\star} \right)^2. \quad (1.4)$$

Therefore, a larger planet will block more light, so it will have a deeper transit, unlike a small planet, which will have a shallower transit, which is harder to detect.

The probability of observing a transit is very small and depends on the geometry of the star-planet system. As such, this technique is very sensitive to exoplanets that orbit closer to their star, since these types of systems are more likely to be in alignment with the observer. Consequently, a large percentage of transiting exoplanets turn out to be "hot Jupiters".²

The *Kepler* space mission (Borucki et al. 2010) was launched by NASA in 2009. *Kepler* observed more than a half million stars in a small portion of the Milky Way. The main goal of this mission was to find Earth-size exoplanets with the transit method. Over 2600 exoplanets were identified, in particular, planets with sizes between Earth and Neptune sizes, demonstrating that these types of planets are very common within the Milky Way (e.g., Borucki et al. 2011; Howard et al. 2012; Petigura et al. 2013). Years later, the Transiting Exoplanet Survey Satellite (TESS) was launched by NASA in 2017 (Ricker et al. 2014), with the goal of searching for exoplanets transiting the brightest stars near the Sun. The PLANetary Transits and Oscillation of stars (PLATO) mission is planned to launch in 2026 and is designed to detect terrestrial planets in the habitable zone of bright solar-type stars.

1.1.3 Other methods

Besides RV and transit methods, other techniques can be used to detect and characterize exoplanets.

Pulsar timing provided the first exoplanet detection around a pulsar (Wolszczan and Frail 1992). Pulsars are rapidly rotating neutron stars formed during supernova explosions. They emit electromagnetic radiation that is detected on Earth as a highly regular and precise pulsation signal. If a planet orbits a pulsar, this can be determined by timing irregularities in the pulsar, which show that the pulsar is moving around the system's mass centre.

²Jupiter-like planets that orbit close to their star

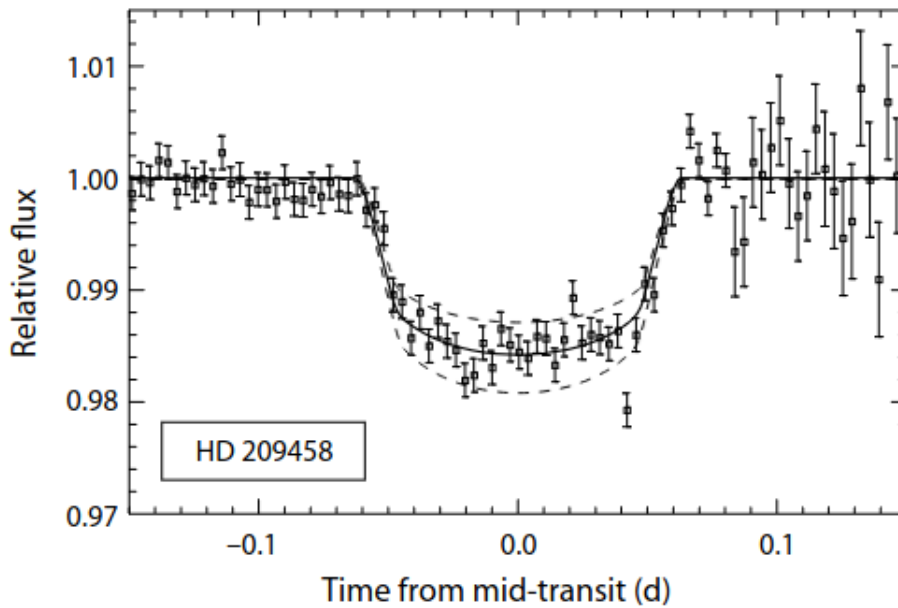


Figure 1.3: Light curve of the first detected transiting exoplanet, HD 209458, reproduced by Perryman [2011](#).

Another effective method for exoplanet detection is gravitational microlensing (Tsapras [2018](#)). It is based on the fact that the light from a distant object (the source) is bent by the gravitational potential of a foreground object (the lens). This was first predicted by Albert Einstein. In this case, the planetary system acts as the lens, and a distant star acts as the source. Although a higher planetary mass will lead to a greater gravitational lensing effect, this method can also detect less massive planets (Han et al. [2022](#)). Another advantage of microlensing is the detection of planets orbiting stars extremely far away from Earth.

Direct imaging is another powerful method for exoplanet detection, yet one of the most difficult methods (Houll   et al. [2021](#)). It consists of blocking out the light of a star that could potentially host a planet. As such, the planet has to be at great distances from its star, since the star will outshine any close planet.

As of today, the least effective method for finding exoplanets is astrometry. This technique measures minute shifts in the star’s position as it revolves around the system’s centre of mass. To find such small variations in the star’s position, this method needs to be extremely precise. Gaia Collaboration et al. [2016](#) is expected to detect thousands of exoplanets with this technique.

1.2 Star-Planet Connection

Today, it is known that planet formation is a universal process that occurs around the majority of the stars (e.g., Cassan et al. [2012](#)). Planets and their host stars are formed from the same

molecular cloud. In particular, planets are born in a disc of gas and dust that surrounds a newly formed star, called *protoplanetary disc*. The properties of the protoplanetary discs are shaped by the properties of the stars, which, in turn, reflect the properties of the Interstellar Medium (ISM) where they were born. The environmental conditions where the stars are formed and the properties of protoplanetary systems play a crucial role in the physical processes occurring during the formation of exoplanets and, in turn, shape their properties and architectures. Thus, some of the properties of planets and their host stars are intrinsically related.

The next Sections delve into the characterization of the detected exoplanets and explore the formation processes and environmental conditions that constrain their properties.

1.2.1 Characterizing exoplanets

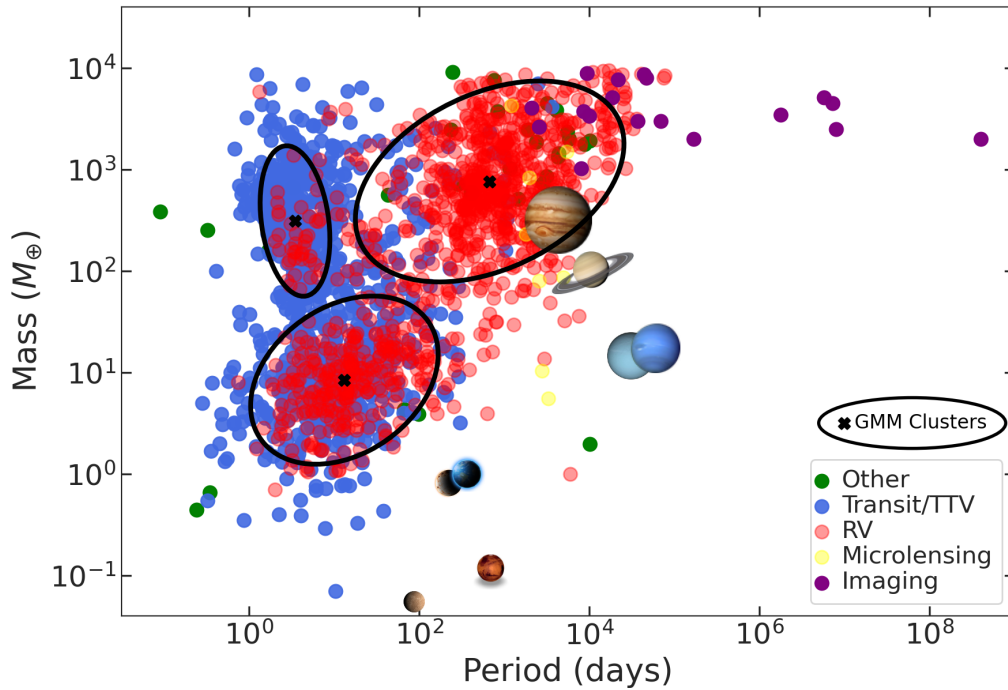


Figure 1.4: Mass-period diagram of the exoplanets discovered. The detection methods are shown using different colors. A Gaussian Mixture Model (GMM) clustering was performed to identify 3 clusters of planets in the diagram. The planets of the Solar-System are also represented. Source: <https://github.com/vadibekyan/ExoPLots.git>

The classification of planets generally encompasses three main composition classes: gas, ice, and rock. Each planet comprises varying proportions of these components based on factors such as planetary mass, formation history, and subsequent evolutionary processes (Russell 2013, 2021). The terms used to characterize exoplanets are vast in the literature. Usually, this classification is based on solar system analogues, such as Gas Giants (Jupiter-like planets), Ice planets (Neptune-like planets), and rocky planets (Earth and Super-Earth-like planets, depending on their mass). However, due to degeneracy in determining interior structure and bulk composition, and the mass

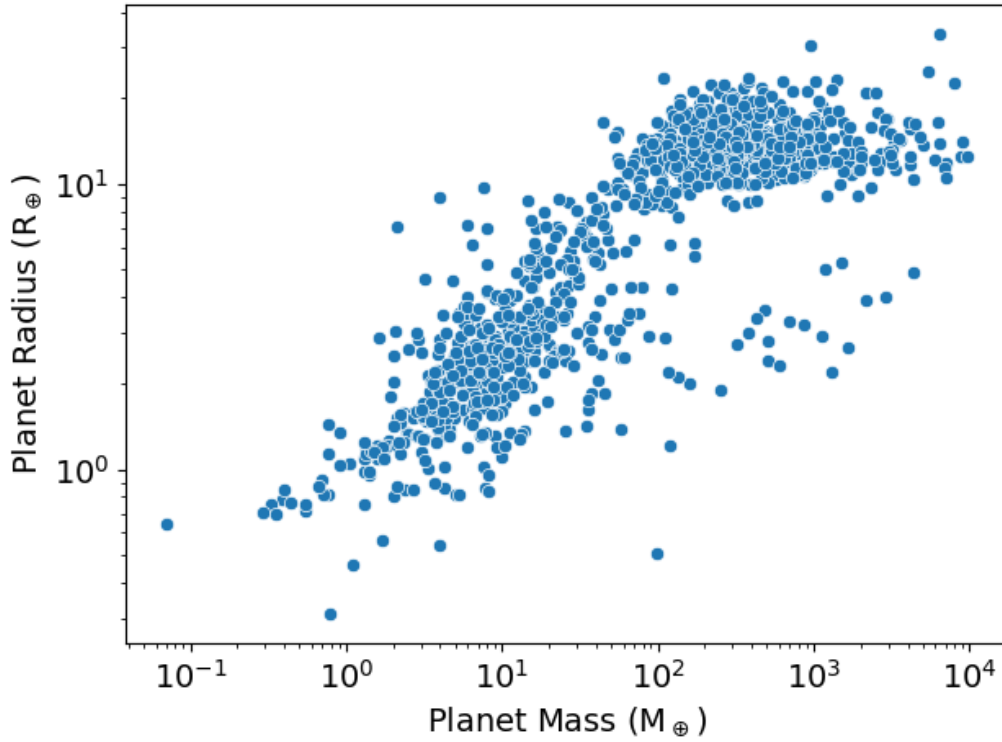


Figure 1.5: Mass-radius diagram of the discovered exoplanets. Data taken from NASA Exoplanet Archive as of 04/08/2023.

range overlap for different compositions, it is very difficult to characterize exoplanets (Russell 2013, 2021).

The mass-period diagram (figure 1.4) of the detected exoplanets as of today shows that exoplanets are clustered mainly in three groups: Super-Earths and Neptune-like planets with $M_p \sim 10M_\oplus$ and $P \lesssim 100$ days; Ice and Gas giants with $M_p \sim 800M_\oplus$ and $P \gtrsim 1000$ days; Hot Jupiters with $M_p \sim 300M_\oplus$ and $P \lesssim 10$ days. The observable absence of giant planets observed between 10-100 days (known as the "period-valley") is believed to be associated with the migration of massive planets within the disc. Additionally, the observed lack of intermediate-mass planets with masses between 10 and 100 $M_\oplus$ (known as the "planetary desert") is explained by the core accretion model (see Section 1.2.2).

In the figure 1.5 is shown that for exoplanets with masses up to $\sim 100 M_\oplus$ the planetary mass increases with planetary radius. However, above that limit, the planet's radius appears to be constant for large values of planetary mass.

It is important to note that these two diagrams have selection effects and observational biases. Still, they provide important information about the physical processes acting during the formation and evolution of exoplanets. A brief overview of the planetary formation models is included in the next Section.

1.2.2 Planetary formation models

The most commonly accepted models for planet formation are core accretion (CA) and gravitational instability (GI).

In the CA scenario, gas and dust present in the protoplanetary disc coagulate to form kilometre-sized planetesimals, which combine to form rocky planets and solid cores of gas giants (Pollack 1984). When these bodies are massive enough, they attract disc gas and form hydrostatic atmospheres. If these cores reach a critical mass of $M_c \sim 5 - 10 M_\oplus$ fast enough (Hasegawa and Pudritz 2014; Ikoma et al. 2000), the pressure gradient in the atmosphere of these planets can no longer support its gravity and collapses onto its core (Ida and Lin 2004). This collapse triggers a phase of rapid gas accretion until the protoplanetary disc dissipates and a gas giant planet is formed. However, if a massive core cannot be formed fast enough until the protoplanetary disc dissipates, a low-mass rocky planet is formed.

This model explains the "planetary desert" observed in figures 1.4 and 1.5. Basically, since the runaway gas accretion when the planet reaches the critical mass happens very quickly, unless the gaseous disc does not dissipate while the planet is forming, the mass of the planet transits very rapidly from $10 M_\oplus$ to $100 M_\oplus$ (Ida and Lin 2004).

In this scenario, the amount of dust present in the protoplanetary discs is related to the efficiency of the formation of planets. Therefore, a higher amount of dust in protoplanetary discs leads to a higher efficiency in the formation of cores that reach the critical mass and, thus, the formation of gas giants.

GI is another widely accepted model and was introduced by Kuiper 1951 to explain the formation of planets in the Solar System. In this model, if the protoplanetary disc is massive and cool enough, the denser portions of it may have insufficient pressure to counteract gravity and rapidly fragment into self-gravitating-bound structures of gas and dust (Boss 1997), which quickly collapse to form giant planets, much before the gas in the disc depletes.

These mechanisms directly affect the characteristics of the planets, however, environmental conditions also play an important role in where these planets are formed.

1.2.3 Planet-Metallicity Relation

Metallicity is a term used to quantify the amount of metals in stars. In astronomy, metals are all the chemical elements heavier than hydrogen and helium.

The abundance of an element in a star is generally presented relative to the Sun using the logarithmic abundance of H, which by definition is set to $\log \epsilon(\text{H}) \equiv 12$, and is usually set in squared brackets, $[\text{m}/\text{H}]$ (Adibekyan 2019). The metallicity of a star, often indicated by its iron abundance, is directly connected to the metal mass fraction Z , and to the hydrogen mass fraction

X , through the following expression,

$$[\text{Fe}/\text{H}] = \log \left(\frac{Z}{X} \right)_* - \log \left(\frac{Z}{X} \right)_\odot. \quad (1.5)$$

Gonzalez 1997 was the first to realise that metal-rich stars have a higher probability of hosting giant planets. This connection, known as the giant planet-metallicity correlation, is currently well established (e.g., Fischer and Valenti 2005; Mortier et al. 2013; Santos et al. 2000, 2004). Unlike high-mass planets, this correlation is not found for low-mass planets (Adibekyan 2019; Udry and Santos 2007). This can be explained by the low detectability of these planets, making it challenging to determine conclusively whether their formation depends on metallicity or not.

Adibekyan 2019 found that stars hosting only low-mass planets have lower $[\text{Fe}/\text{H}]$ than stars hosting at least one low-mass planet, but slightly higher than single stars (stars without any detected planet). However, no significant statistical difference was found in the $[\text{Fe}/\text{H}]$ distributions of stars hosting only low-mass planets and single stars, contrary to stars hosting at least one low-mass planet and single stars. These results are presented in figure 1.6.

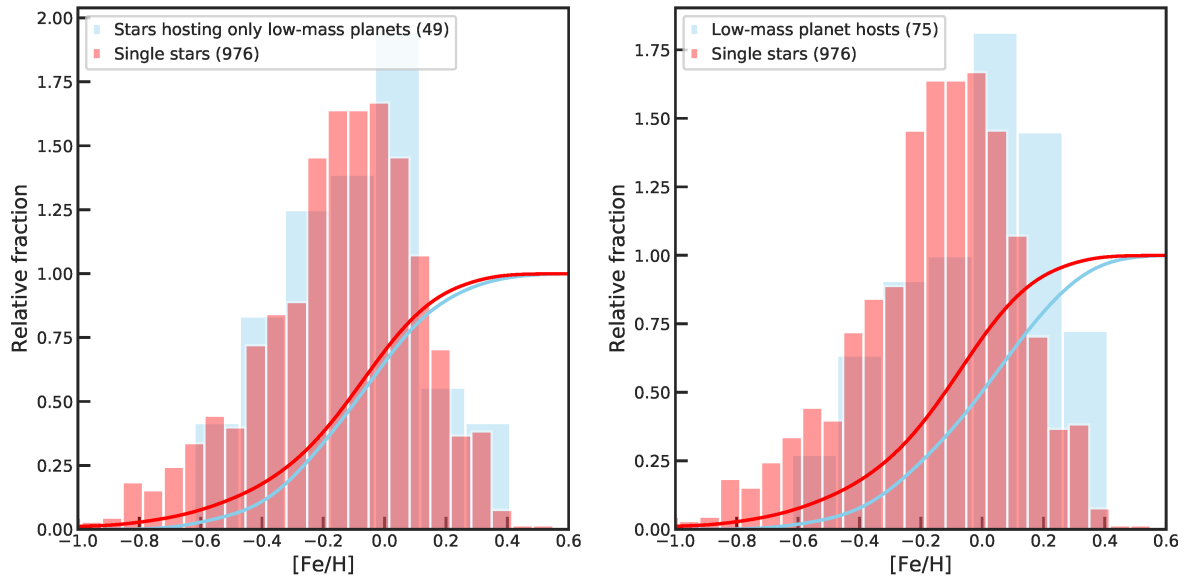


Figure 1.6: Metallicity distributions of stars hosting only low-mass planets (*left panel*, blue), stars hosting at least one low-mass planet (*right panel*, blue), and stars without any detected planets (*left and right panels*, red). The corresponding cumulative distribution of metallicity is illustrated by the kernel density estimation (KDE) curves in matching colours. From Adibekyan 2019.

To explain the origin of the observed abundance of metals in stars hosting giant planets, two hypotheses have been proposed. The first is the self-enrichment hypothesis (e.g., Gonzalez 1997; Laughlin and Adams 1997), suggesting that planetary material from the disc is absorbed by the outer envelope of the star, potentially facilitated by the inward migration of massive planets that carry metal-rich material with them. However, this process alone may not fully account for the observed increase in metallic content. The second and more plausible explanation is the

primordial origin hypothesis (e.g., Fischer and Valenti 2005; Santos et al. 2004), proposing that the high stellar metallicity is likely a consequence of these stars being formed in high metallicity environments, where the amount of dust is expected to be higher, and, in turn, favouring the formation of gas giant planets, as predicted by CA models. Therefore, a higher metallicity in these stars is related to a higher occurrence of giant planets.

1.3 Motivation of the work

The ISM from which stars are formed is far from being homogeneous and isotropic. Stars are formed in dense and cold regions of the ISM. Throughout their lives, they produce heavier and heavier elements in their interiors. At the end of their lives, they eject these elements into the ISM through mass loss or supernova explosions. These contribute to the enrichment of the ISM over time and make the next generations of newly formed stars more metallic than the previous ones (Matteucci 2021). Besides, a negative radial metallicity gradient of ~ -0.07 dex kpc⁻¹ (e.g., Minchev et al. 2018) is also observed today in the Galaxy’s disc, which is believed to be the result of an inside-out formation of the Milky Way’s disc.

However, stars do not remain in the same orbit around the centre of the Galaxy during their lifetime. In fact, stars tend to radially migrate from their birthplace to another galactocentric radius without leaving a dynamical trace (Sellwood and Binney 2002). The radial migration of stars occurs on timescales of Gyrs, while the formation of planetary systems generally happens a few Myr after the star is born. This means that the planets were formed before the host stars had time to radially migrate in the Galaxy.

As discussed, the environment in which stars are born within the Galaxy plays a crucial role in the formation and evolution of their planets. However, the locations at which planetary systems are observed today do not represent the environments from which they were formed. The main goal of this work is to infer the Galactic birthplaces of exoplanets, understand Galactic aspects of exoplanet formation and occurrence, and how they influence their properties. Determining the Galactic birthplaces of stars is also the key to understanding Galactic formation and evolution, taking into account radial migration.

In this work, the method developed by Minchev et al. 2018 was implemented to estimate the Galactic birthplaces of stars. By reconstructing a model of the evolution of ISM metallicity over time and galactocentric distance, the Galactic birthplaces of the exoplanets can be inferred from estimates of stellar metallicities and ages.

Chapter 2 is dedicated to the description of the stellar samples and data used in this work. Chapter 3 contains the methods and tools used to estimate stellar ages. Chapter 4 provides an overview of how to infer Galactic birthplaces, r_{birth} , of exoplanets, describes the method used for that estimation, and presents the results obtained, followed by a discussion. Finally, a summary of the work and conclusions can be found in Chapter 5.

Chapter 2

Data Collection and Samples Description

The first step to constraining the observational properties of the stars is to look for astrometric, photometric, and spectroscopic data. This Chapter provides a description of the data collection and samples used in this work.

2.1 Astrometry and Photometry

Astrometry measures the parallax, positions, and proper motions of astronomical objects. The parallax, p , is the angle difference of an object seen from two different positions. If the parallax is measured, the distance, d , of a star can be inferred as

$$d \simeq \frac{1}{p}, \quad (2.1)$$

where the distance is measured in parsec and the parallax in arcseconds.

Photometry yields measurements of the brightness of the stars, i.e., the flux radiated from the stars, detected by photometers in different wavelength bands or filters F_λ . These are usually expressed in terms of the apparent magnitudes of the stars at a given wavelength, m_λ as

$$m_\lambda = -2.5 \log_{10} \left(\frac{F_\lambda}{F_\lambda^0} \right), \quad (2.2)$$

where F_λ^0 is the zero point reference flux in that wavelength.

Astrometric and photometric measurements can be collected from large-scale surveys that contain different photometric characteristics, which limits them to cover a selected wavelength range. Among all the existing surveys, 2MASS and *Gaia* stand as preeminent cornerstone missions in astronomy for their contribution on mapping the Milky Way and providing an understanding of its origin, structure, and evolution.

In Sections 2.1.1 and 2.1.2 a description of these two surveys is provided.

2.1.1 2MASS

The Two Micron All-Sky Survey (2MASS; Skrutskie et al. 2006) observed the sky between 1997 and 2001 in three near-infrared photometric bands (J (1.235 μm), H (1.662 μm), and K_s (2.159 μm), as seen in figure 2.1), for which observations were conducted from two 1.3 m ground-based telescopes located at Mount Hopkins, Arizona, and Cerro Tololo, Chile. These observations resulted in a catalogue of over 400 million point sources.

The wavelength choice of this survey was limited by atmospheric transmission and ambient thermal background radiation. Therefore, choosing the longest wavelength atmospheric window, the K_s -band (Johnson 1962), would remain relatively unaffected by these effects.

Furthermore, being a near-infrared survey, 2MASS has the ability to penetrate interstellar extinction (see Section 3.2) and provide precise photometry. Consequently, it unveils the true mass distribution and, in turn, the large-scale structure of the Milky Way and the Local Universe (Jarrett 2004).

2.1.2 *Gaia* mission

Just until the mid-1990s, measurements of positions and parallaxes were made with ground-based instruments, which was extremely challenging due to the distorted effects caused by atmospheric seeing of Earth.

The situation changed with the launch of *Hipparcos* satellite (Perryman 1982) of the European Space Agency (ESA), which measured positions, parallaxes, and proper motions of 117 955 stars with milliarcsecond accuracy. In 2000, ESA developed a cornerstone mission, *Gaia* (Gaia Collaboration et al. 2016), with the goal of measuring parallaxes of more than 1 billion sources with a precision one hundred times better than that of *Hipparcos*.

The *Gaia* satellite was launched in 2013 and scans the entire sky periodically from its orbit around the Sun, located at the L_2 Lagrangian point. The payload of *Gaia* is composed of three main instruments: i) the astrometric instrument, which collects images in the broad band G (330-1050 nm) (see figure 2.1), measuring the positions of the stars and in turn the parallaxes; ii) the photometric instrument, constituted by the blue BP (330-680 nm) and red RP (649-1050 nm) prism photometers that collect the spectral energy distribution of all detected objects at the same angular resolution and at the same epoch as the astrometric observations; iii) and a spectroscopic instrument, known as the radial-velocity spectrometer (RVS), which obtains spectra of the bright end of the *Gaia* sample to provide radial velocities through Doppler-shift measurements.

Gaia Data Release 3 (DR3; Gaia Collaboration et al. 2022) contains photometry and astrometry for 1.8 billion sources in the Milky Way.

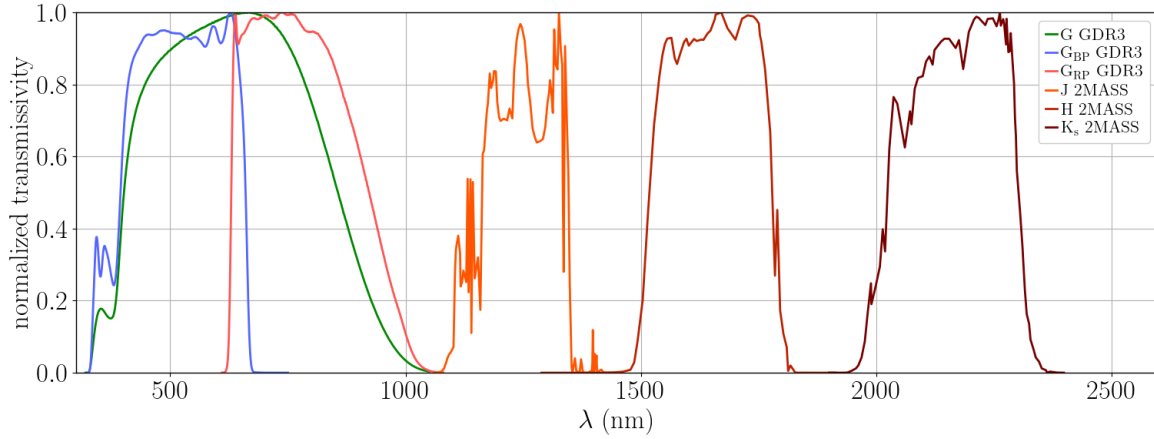


Figure 2.1: Normalized passbands of the *Gaia* G , G_{BP} and G_{RP} filters, and 2MASS J , H and K_s filters.

2.2 Spectroscopy

Spectroscopy is the study and analysis of the spectrum of astronomical sources. Stars emit blackbody-like radiation produced in their cores - radiation that produces a continuous spectrum. However, the chemical elements present in their upper layers (the photosphere) absorb the radiation emitted by the stars at specific wavelengths. Therefore, the observed spectrum is a continuous spectrum with absorptions, which is unique for each star. The spectrum of a star not only reveals the presence of certain chemical elements but also informs about other stellar parameters, such as metallicity, $[Fe/H]$, effective temperature, T_{eff} , and surface gravity, $\log g$.

A homogeneous and uniform spectral analysis is necessary to reduce uncertainties in the stellar atmospheric parameters (Adibekyan 2019). The derivation of stellar parameters using a uniform methodology is presented in some catalogues, such as SWEET-Cat, CKS, and HARPS-GTO.

SWEET-Cat¹ (Santos et al. 2013; Sousa et al. 2021) is a catalogue of stellar parameters of stars with planets listed in The Extrasolar Planets Encyclopaedia², exclusively detected by RV, transit, and astrometry methods. This catalogue compiles atmospheric stellar parameters, such as $[Fe/H]$, T_{eff} , and $\log g$, derived from the literature ('SWFlag = 0'), and, whenever possible, derived using a uniform spectral analysis ('SWFlag = 1'), prioritising high-resolution and high signal-to-noise ratio (SNR) spectra for each host star. Besides, this catalogue also includes uniformly trigonometric $\log g$ derived from *Gaia* parallaxes using the method of Santos et al. 2004.

The California-Kepler Survey (CKS) (Petigura et al. 2017) is an observational program with the goal to measure precise spectroscopic stellar parameters, with a uniform set of high-resolution and high SNR spectra, of stars found to host transiting planets discovered by the *Kepler* Mission.

¹<http://sweetcat.iaastro.pt/>

²<http://exoplanet.eu/>

From the HARPS-GTO planet search programs, a catalogue containing nearby 1111 FGK stars with atmospheric stellar parameters $[\text{Fe}/\text{H}]$, T_{eff} and $\log g$, derived using a uniform methodology, was described in Adibekyan et al. 2012 and Delgado Mena et al. 2017. This catalogue also includes trigonometric $\log g$ derived from *Hipparcos* parallaxes, using the method of Santos et al. 2004. This catalogue is composed of 136 stars with planets and 975 stars without detected planets. The catalogue is available online³.

2.3 Samples

For this work, two distinct samples of stars hosting planets and a sample of stars without detected planets were selected:

- From the SWEET-Cat catalogue, host stars with homogeneously ('SWFlag = 1') determined $[\text{Fe}/\text{H}]$, T_{eff} and trigonometric $\log g$ were selected. Since the provided uncertainties represent the precision, a factor of 0.04 dex in $[\text{Fe}/\text{H}]$, 60 K in T_{eff} and 0.1 dex in $\log g$ were added to take into consideration systematic uncertainties (see Sousa et al. 2011). This constitutes the SWEET-Cat sample in this work;
- From the CKS program, host stars with homogeneously determined $[\text{Fe}/\text{H}]$, T_{eff} and spectroscopic $\log g$ were selected. Systematic uncertainties were added quadratically to the precision uncertainties of these quantities as suggested by Petigura et al. 2017: 100 K in T_{eff} and 0.04 dex in $[\text{Fe}/\text{H}]$. This constitutes the CKS sample in this work;
- From the HARPS-GTO catalogue, only stars without any detected planets with homogeneously determined $[\text{Fe}/\text{H}]$, T_{eff} , trigonometric $\log g$ were selected. Systematic uncertainties were added quadratically to the precision uncertainties of these quantities: 0.04 dex in $[\text{Fe}/\text{H}]$, 60 K in T_{eff} and 0.1 dex in $\log g$. The stars without any detected planets in HARPS-GTO were selected by performing a crossmatch with the SWEET-Cat catalogue, in order to identify and, subsequently, remove stars known to harbour planets. This constitutes the HARPS sample in this work.

In order to obtain the planetary properties of the planets that constitute SWEET-Cat and CKS samples, a crossmatch between these samples and the NASA Exoplanet Archive was performed using *Gaia* Data Release 2 (DR2; Gaia Collaboration et al. 2018) identifications. The best estimate of the planetary mass M_p , planetary radius R_p , orbital period P , and associated uncertainties were obtained from the NASA Exoplanet Archive.

To obtain the properties of the stars, the photometric data was selected from 2MASS K_s band magnitudes and their uncertainties, and from *Gaia* DR3, for which it contains mean photometric magnitudes in G , G_{BP} , and G_{RP} bands and their respective mean flux over error, $\Delta F/F$. The

³<http://vizier.cds.unistra.fr/viz-bin/VizieR?-source=J/A+A/606/A94>

uncertainties for each *Gaia* passband were computed from the propagation of errors,

$$\Delta G = \sqrt{\left(\frac{-2.5}{\ln 10} \cdot \frac{\Delta f}{f}\right)^2 + \sigma_X^2}, \quad (2.3)$$

where σ_X is the zero point uncertainty in the VEGAMAG system, which allows for the transformation of internally calibrated source fluxes into magnitudes (Riello et al. 2021). For each passband, we have X^4 : $\sigma_{G_0} = 0.0027553202$, $\sigma_{BP_0} = 0.0027901700$, and $\sigma_{RP_0} = 0.0037793818$.

The parallaxes were obtained from *Gaia* DR3. An important note is that only stars with parallax with relative uncertainties smaller than 10% were selected. Since there is a nonlinear relationship between parallax and distance, a significant uncertainty in parallax measurement can lead to a notable bias in the distance estimation (Astraatmadja and Bailer-Jones 2016).

All photometric and astrometric data used in this work are available through *Gaia* Archive⁵.

In the next subsection, a description of the stellar and planetary properties of the samples is provided. It is important to note that the stars that comprise these samples are the ones with estimated ages, thus the final samples. The determination of stellar ages is studied in Chapter 3.

2.3.1 SWEET-Cat Sample

The SWEET-Cat final sample has 624 stars hosting 842 exoplanets located within 2 kpc from the Sun. Figure 2.2 shows the distribution of T_{eff} , $[\text{Fe}/\text{H}]$, and $\log g$ of the host stars. The stars are mainly FGK stars with a T_{eff} range from 4278 to 7201 K. It shows a wide range in $\log g$, from 1.78 to 4.93 dex, however, most of the stars are in the main sequence ($4 \lesssim \log g \lesssim 5$ dex), and only a few are evolved stars ($\log g \lesssim 4$ dex), corresponding to sub-giants and red giants. Regarding $[\text{Fe}/\text{H}]$, the sample shows a wide dispersion from -0.74 to 0.55 dex, yet it is more concentrated towards the solar and super-solar values, with a mean of $[\overline{\text{Fe}/\text{H}}] = 0.12$ dex.

The exoplanets of this sample were detected mostly by transit (422) and RV (414) methods. With other methods 6 planets were detected. It is important to note that while the catalogue initially covers stars with planets detected using RV and transit method, the crossmatch also revealed planets detected using different methods for the same stars. The same applies to the CKS sample (see sub-section 2.3.2).

The distributions of the properties of the exoplanets present in this sample are shown in figure 2.3. The detection methods of these planets are represented using different colors. For planetary masses, the distribution spans a range between $0.8 M_{\oplus} \lesssim M_p \lesssim 6884 M_{\oplus}$.⁶ In this sample, the "planetary desert" is observed between super-Earth masses and Jupiter masses (discussed in Sections 1.2.1 and 1.2.2). It is also noticeable the bias towards high-mass planets for the RV method.

⁴<https://www.cosmos.esa.int/web/gaia/edr3-passbands>

⁵<https://gea.esac.esa.int/archive/>

⁶Note that some of these companions are not planets, but brown dwarfs with $M_p > 13 M_J$ ($\approx 4134 M_{\oplus}$).

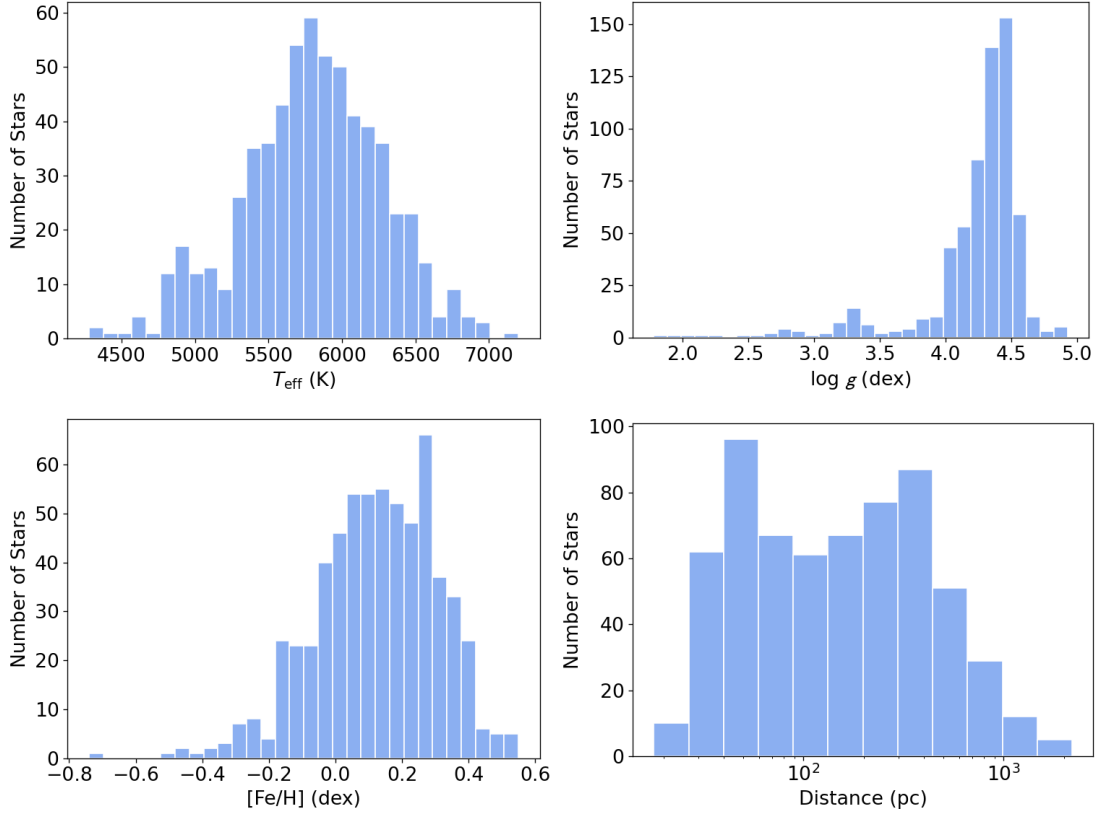


Figure 2.2: The SWEET-Cat sample: distribution of T_{eff} , $[\text{Fe}/\text{H}]$, $\log g$ and distance.

Regarding planetary radii distribution, it falls within the interval $0.3 R_{\oplus} \lesssim R_p \lesssim 33 R_{\oplus}$, and it is primarily shaped by transit planets, since they are the ones with derived radii. There are two peaks seen in this distribution: one around small-sized planets ($\sim 2 R_{\oplus}$), since these planets ($R_p \lesssim 4 R_{\oplus}$) are more common than large planets; the other peak is around large planets, which is due to the detection bias of the transit method towards planets with larger radii.

The orbital period distribution ranges between $0.4 \text{ days} \lesssim P \lesssim 18208 \text{ days}$. Planets with a short orbital period were detected mainly with transit, since close-in planets have a higher probability of transiting, whereas planets with a high orbital period were detected with the RV method.

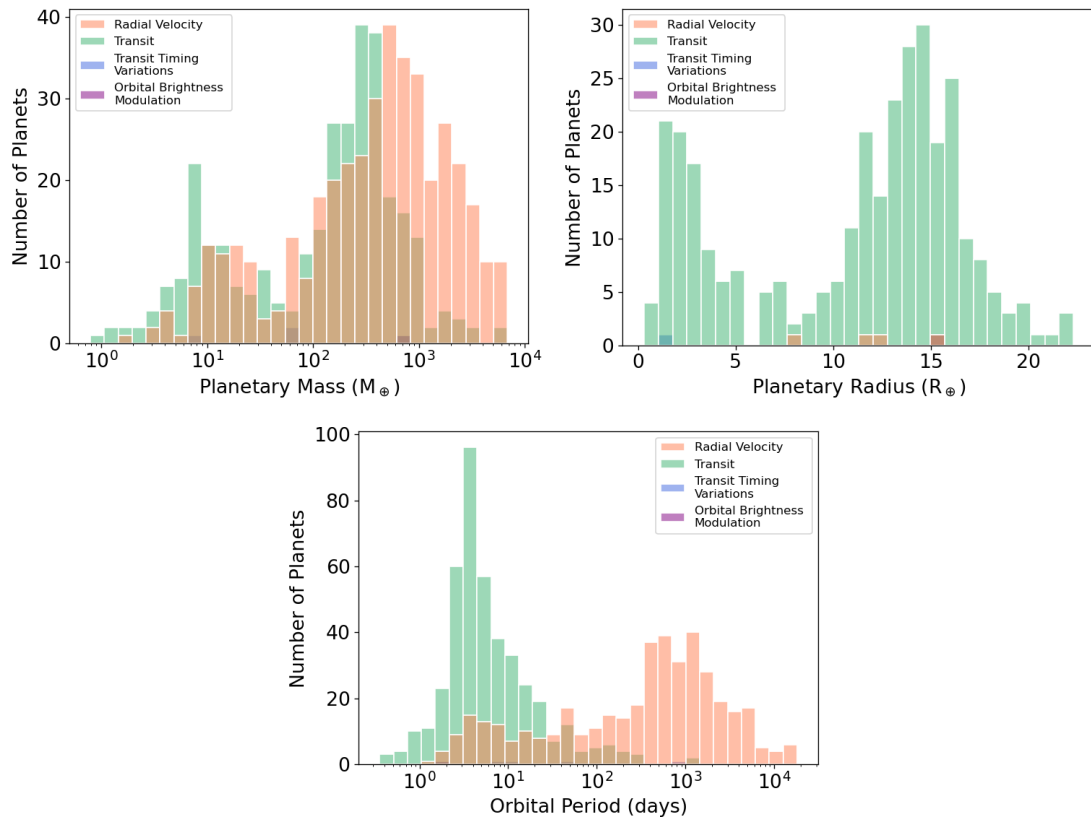


Figure 2.3: The SWEET-Cat sample: distribution of planetary mass, planetary radius and orbital period.

2.3.2 California-Kepler Survey Sample

The CKS final sample is composed of 581 stars hosting 1021 exoplanets located within ~ 108 pc to ~ 2.5 kpc. The stars have a T_{eff} range from 4653 to 6563 K, a $\log g$ from 3.38 to 4.79 dex, and a $[\text{Fe}/\text{H}]$ from -0.43 to 0.44 dex, with a mean $[\text{Fe}/\text{H}] = 0.06$ dex, which is close to the solar value (figure 2.4).

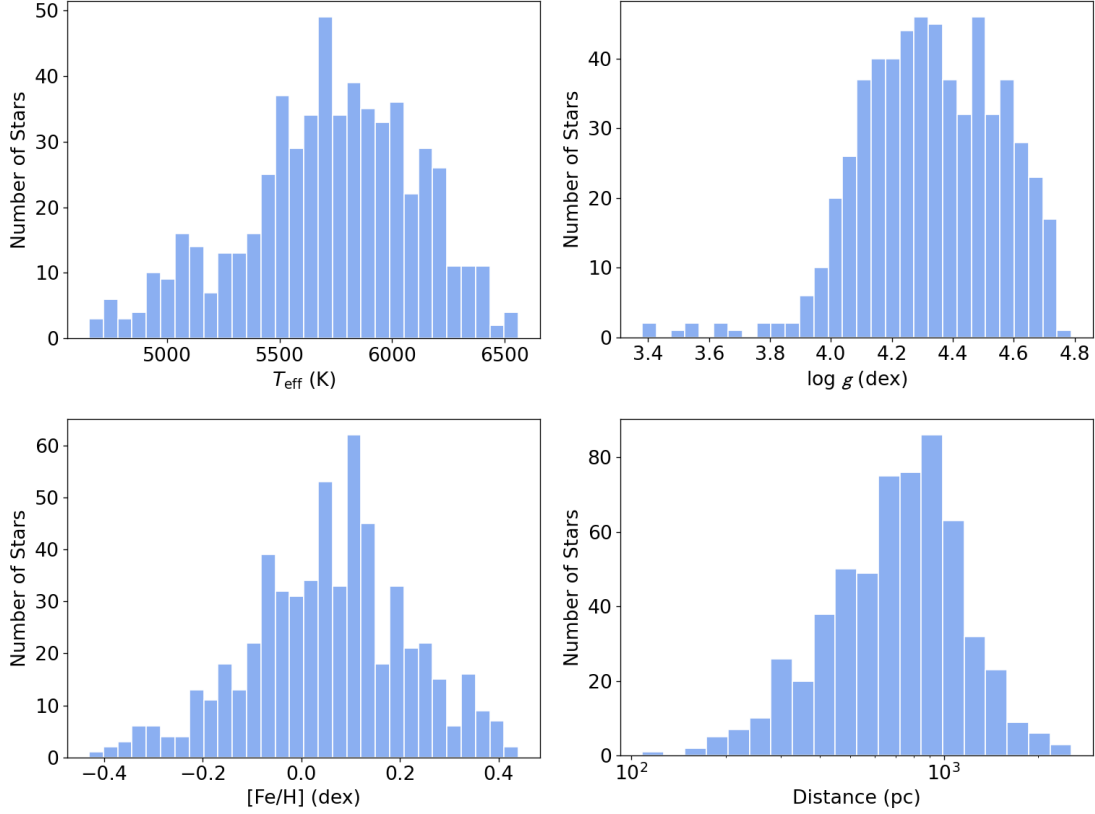


Figure 2.4: The CKS sample: distribution of T_{eff} , $[\text{Fe}/\text{H}]$, $\log g$ and distance.

The exoplanets present in this sample were detected mostly by the transit method (1006). Nine exoplanets were detected with RV, and six planets were detected by other methods.

The distributions of the properties of the exoplanets present in this sample are shown in figure 2.5. The planetary mass distribution ranges between $0.8 M_{\oplus} \lesssim M_p \lesssim 4386 M_{\oplus}$, the radius ranges from $0.5 R_{\oplus} \lesssim R_p \lesssim 19.7 R_{\oplus}$, and the orbital period ranges from $0.6 \text{ days} \lesssim P \lesssim 4073 \text{ days}$. However, the planets are more clustered towards small values in mass, radius, and orbital period. Additionally, it is important to note that the majority of planets in this sample do not have derived masses.

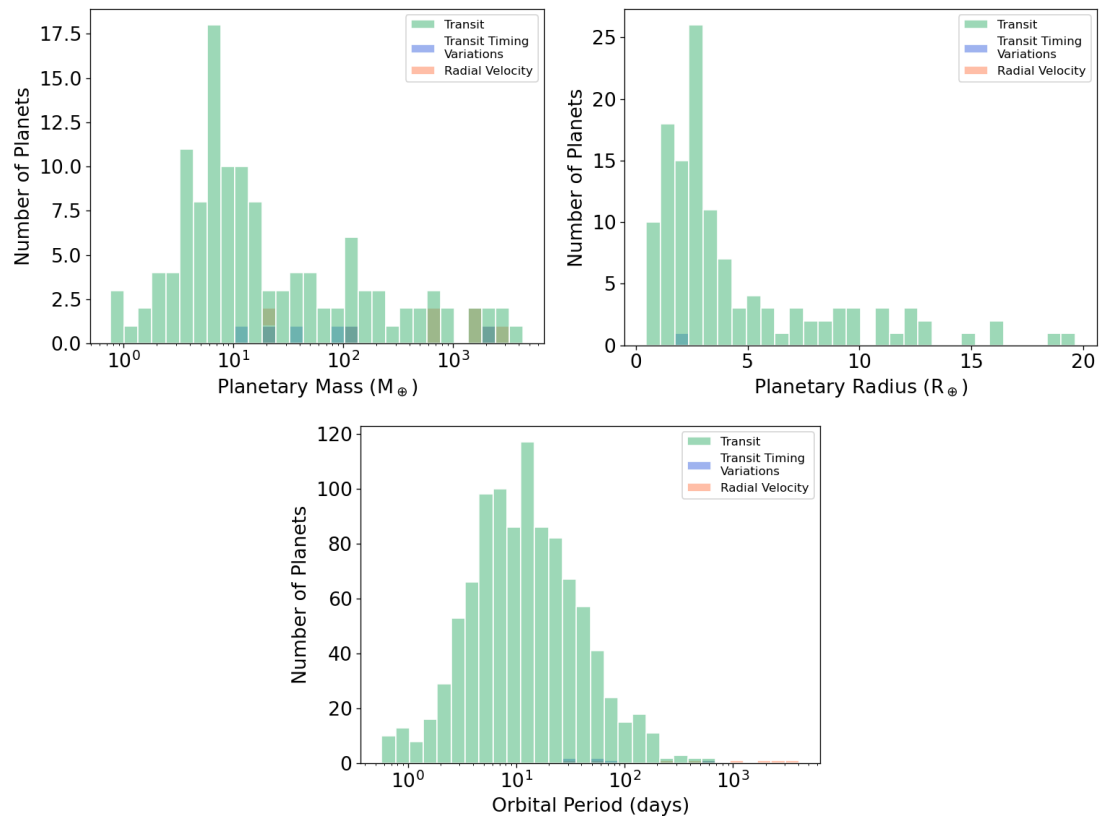


Figure 2.5: The CKS sample: distribution of planetary mass, planetary radius and orbital period.

2.3.3 HARPS Sample

The HARPS sample is composed of nearby 492 stars located within ~ 591 pc from the Sun. The stellar property distributions are shown in figure 2.6. The sample has T_{eff} within a range from 4470 to 7212 K. Regarding the $\log g$ distribution, it varies from 1.72 to 4.76 dex but is more concentrated at main-sequence values. The $[\text{Fe}/\text{H}]$ distribution ranges from -1.39 to 0.45 dex, however, the majority of the values cluster around the solar value, as indicated by an average of $\overline{[\text{Fe}/\text{H}]} = -0.08$ dex.

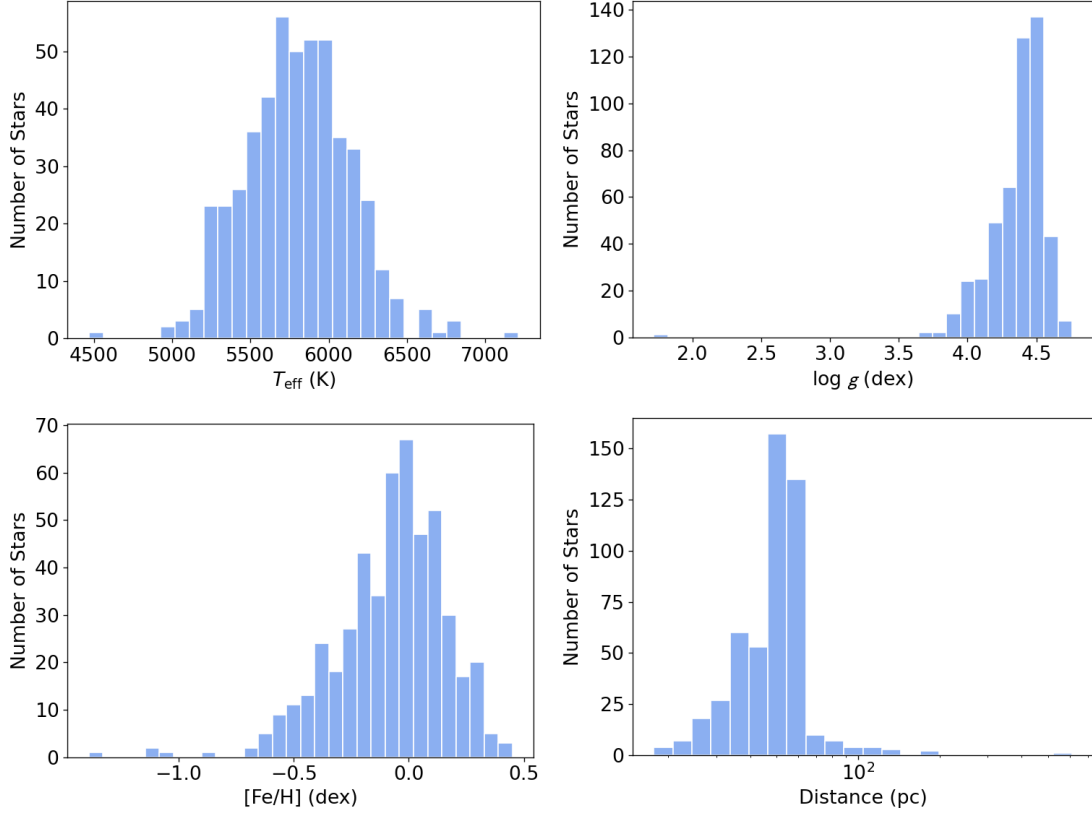


Figure 2.6: The HARPS sample: distribution of T_{eff} , $[\text{Fe}/\text{H}]$, $\log g$ and distance.

Chapter 3

Stellar Ages

This Chapter focuses on the determination of stellar ages for the stars in the three samples described in Section 2.3. In the first Section of this Chapter, a description of the available methods for measuring stellar ages is provided, with a focus on the approach adopted in this work. The methods and tools used for computing the relevant parameters for measuring stellar ages are thoroughly explained.

3.1 Methods of stellar age determination

The determination of stellar ages is a crucial step in understanding stellar evolution, galactic archaeology, and the study of exoplanets.

However, measuring stellar age is a very challenging process. The main methods used to infer ages are empirical relations, data-model comparison, and statistical methods. Each method works for specific stellar types and ranges in age. The description of these methods is detailed in the review of Soderblom [2010](#).

Empirical methods rely on how certain properties can change during stellar evolution. This is the case of gyrochronology (Barnes [2003](#)), stellar activity, and lithium depletion (Skumanich [1972](#)). Statistical methods are based on galactic trends that relate to stellar ages, namely, the abundance-age relation and the increase of Galactic space motions. Among the three methods, the data-model comparison methods are the primary approach used for age estimation. These consist of comparing the observational properties of the stars to the theoretical ones predicted by stellar structure and evolution models. The most commonly used method is isochrone fitting (Jørgensen and Lindegren [2005](#); Nordström et al. [2004](#); Pont and Eyer [2004](#)).

Stellar ages are inherently uncertain due to the fact that the moment of their birth is not well defined (Soderblom [2010](#)). In fact, the only star that has both precise and accurate determined age is the Sun. The age of the Sun can be measured in such way because of the possibility of analysing solar system material in the laboratory. Bahcall et al. [1995](#) found that the age of the

Sun is $(4.570 \pm 0.006) \times 10^9$ years from radioactive dating of meteorites. Therefore, the solar age is the only benchmark available in all stellar astrophysics. For any other star, such precise and accurate estimation is not possible.

3.1.1 Isochrone fitting

In this subsection it is explained how the isochrone fitting method works. An isochrone is a theoretical curve of stellar luminosity and effective temperature on the Hertzsprung-Russell Diagram (HRD), which represents the evolutionary position of stars with the same age and initial metallicity but different masses. In contrast to an evolutionary track, which plots stars of varying ages but the same mass, isochrones connect stars of the same age along the evolutionary tracks. In figure 3.1 is shown an example of two isochrones of ages 1 Gyr and 5 Gyr, computed with PARSEC (Bressan et al. 2012). The stellar masses are marked at the representative evolving points in each isochrone. Isochrones can be used to determine the age of stellar clusters or individual stars. Stars in stellar clusters are assumed to have formed almost simultaneously in the same molecular cloud, exhibiting some similar properties between each other and, hence, roughly the same age. Since clusters have a significant number of stars, the fitting is improved statistically. Therefore, isochrone fitting is an easier process for stellar clusters than for individual stars.

The evolution of low-mass stars lasts for several billion years, since these stars burn quietly hydrogen in their cores. The determination of their age is very challenging, as a difference of several billion years results in hardly detectable changes in their structure. On the other hand, massive stars only live for hundreds of millions of years. In older isochrones, massive stars are absent, while low-mass stars are still evolving on the main sequence (MS), fusing hydrogen into helium in their cores. In a particular isochrone, more massive stars are in later evolutionary stages.

As stars fuse hydrogen into helium in their cores during the MS phase, the mean molecular weight, μ , increases. To compensate for this increase, the ideal gas law requires that $\rho_c T_c$ increase to keep the star in hydrostatic equilibrium. For that to happen, the core needs to contract and the outer layers to expand, leading to an increase in the radius of the star. The contraction of the core leads to the release of gravitational potential energy, thus increasing luminosity. For all masses, the radius expands as the star evolves, but not at the same rate. However, for low-mass stars with $M_\star \leq 1.3 M_\odot$, the expansion is modest since the main energy-producing reactions are those of the proton-proton (pp) chain. The lower temperature sensitivity ($\epsilon_{\text{pp}} \propto T^4$) means that the temperature and density of the core increase. For stars with $M_\star \geq 1.3 M_\odot$, the expansion of the outer layers is very rapid. These stars fuse hydrogen to helium through the carbon-nitrogen-oxygen (CNO) cycle, which is very sensitive to temperature ($\epsilon_{\text{CNO}} \propto T^{18}$). A small variation in the temperature causes energy production to increase. Isochrones follow up to a mass where the hydrogen has just been exhausted in the core, progressing almost horizontally to the right in what is called the subgiant phase (SG). In this stage, a hydrogen-burning shell is

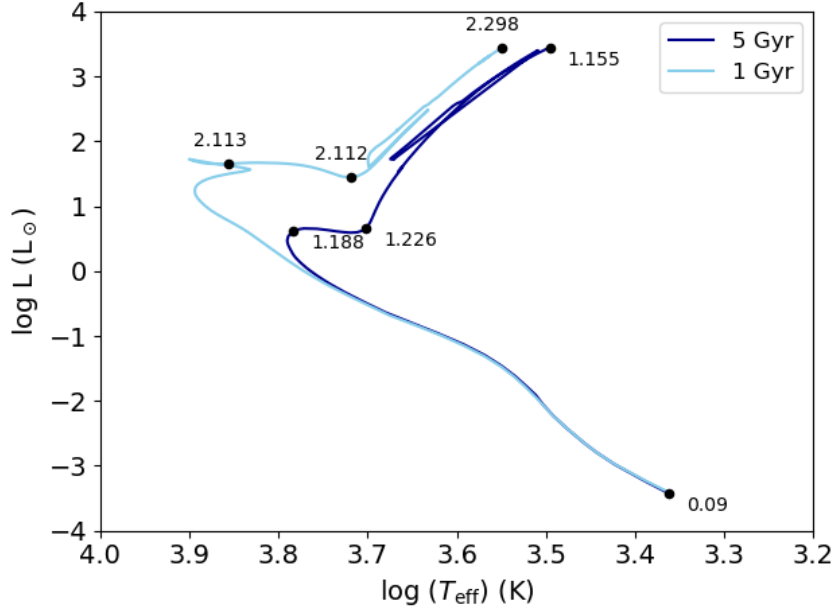


Figure 3.1: Isochrones computed with PARSEC in the HR diagram for 1 Gyr and 5 Gyr. Stellar masses in solar masses are marked in black at the representative evolving points.

formed surrounding an inert helium core. For stars with $M_{\star} \geq 1.3 M_{\odot}$, when the abundance of hydrogen gets low in the core, the CNO reactions diminish, and the temperature has to increase sufficiently to keep up the energy production. This causes a hook feature in the HRD, which is observed for younger isochrones. In the next stages, the process repeats: the star starts to burn helium in the core until it is exhausted, and the hydrogen-burning shell thins, forcing core contraction and outer layer expansion, leading to a significant rise in luminosity and radius, transitioning into the red-giant branch (RGB).

In contrast to general theoretical models, where model parameters are mapped to the observed data, the stellar isochrone fitting method is the inverse problem (Jørgensen and Lindegren 2005; Pont and Eyer 2004). It starts by mapping the observed data - observed or inferred stellar parameters from astrometry, photometry, and spectroscopy - e.g., T_{eff} , $[\text{Fe}/\text{H}]$, and luminosity L , to the model parameter, age τ . Nevertheless, other parameters can also be estimated, such as $M_{\star}$ or $R_{\star}$.

3.1.2 PARAM

Isochrone fitting is usually approached by a probabilistic method, particularly, Bayesian estimation. For this work, a Bayesian isochrone fitting tool, PARAM (da Silva et al. 2006; Rodrigues et al. 2017, 2014), was employed to estimate stellar ages. PARAM makes use of a set of isochrones from PARSEC v1.2 (Bressan et al. 2012), which were re-generated with a very small stepsize in both age and metallicity (Rodrigues et al. 2014).

PARAM can accept several input parameters; however, stellar metallicity is the mandatory

one. For this work, the input measured data, $\mathbf{y}$, consists of T_{eff} , L , $[\text{Fe}/\text{H}]$ and their uncertainties. The determination of stellar luminosity, L , in this work is explained in the next sections of this Chapter. PARAM computes a posterior probability density function (PDF) of the model parameters, $\mathbf{x}$, which consist of τ , M_* , R_* , mean stellar density ρ , absolute magnitude M_λ , and extinction A_λ , in several passbands. From the Bayes theorem, the posterior probability density function is given by:

$$p(\mathbf{x}|\mathbf{y}) = \frac{p(\mathbf{y}|\mathbf{x})p(\mathbf{x})}{p(\mathbf{y})}, \quad (3.1)$$

where $p(\mathbf{x})$ is the joint prior probability function of the model parameters before any data is observed, $p(\mathbf{y})$ is the normalization factor, and since it does not depend on $\mathbf{x}$, it can be ignored, and $p(\mathbf{y}|\mathbf{x})$ is the likelihood of the observed data given the model parameters, which are linked through theoretical isochrones. Assuming that the uncertainties of the measured data are described by a normal distribution, it can be written as:

$$p(\mathbf{y}'|\mathbf{x}) = \prod \frac{1}{\sqrt{2\pi}\sigma_{y_i}} \exp\left(-\frac{(y'_i - y_i)^2}{2\sigma_{y_i}^2}\right), \quad (3.2)$$

where y' represents the mean value of the measured data, while σ_i denotes the standard deviation for each parameter i . To obtain the model parameters, $\mathbf{x}_i$, the posterior PDF is integrated over all the parameters, except for $\mathbf{x}_i$, resulting in a PDF for each parameter. At the end, the median, mode and 68th percentile is computed for each PDF. Figures 3.2 and 3.3 show an example of the PDFs obtained with PARAM of both age and mass, for two different stars 14 Her and EPIC 201295312, respectively. The green line corresponds to the median, and the dashed green lines correspond to the lower and upper 68th percentiles. The blue line represents the mode, and the dashed blue lines are the respective lower and upper 68th percentiles. Contrary to 14 Her, the PDFs for both age and mass obtained with PARAM for EPIC 201295312 show two solutions (figure 3.3). This is a characteristic for stars with $M_* \geq 1.3 M_\odot$ due to the hook feature present in the HRD, leading to degenerate solutions for stars located in this part of the diagram. To best characterize the age of the stars, the median was chosen over the mode since the median is less sensitive to extreme values, in this case, the double solutions in PARAM outputs.

3.2 Reddening and Extinction

Trumpler 1930 was the first to recognize that the presence of interstellar gas and dust cause the scatter and absorption of electromagnetic radiation coming from an astronomical source to an observer. This phenomenon is known as *extinction* and alters the observed apparent magnitude as

$$m_\lambda = m_\lambda^0 + A_\lambda, \quad (3.3)$$

where m_λ^0 is the intrinsic magnitude and A_λ , a positive quantity measured in magnitudes, is known as the extinction at wavelength λ .

Extinction changes the observed characteristics of distant objects, causing them to appear dimmer and redder. The *reddening* of the sources is caused by the fact that dust grains scatter

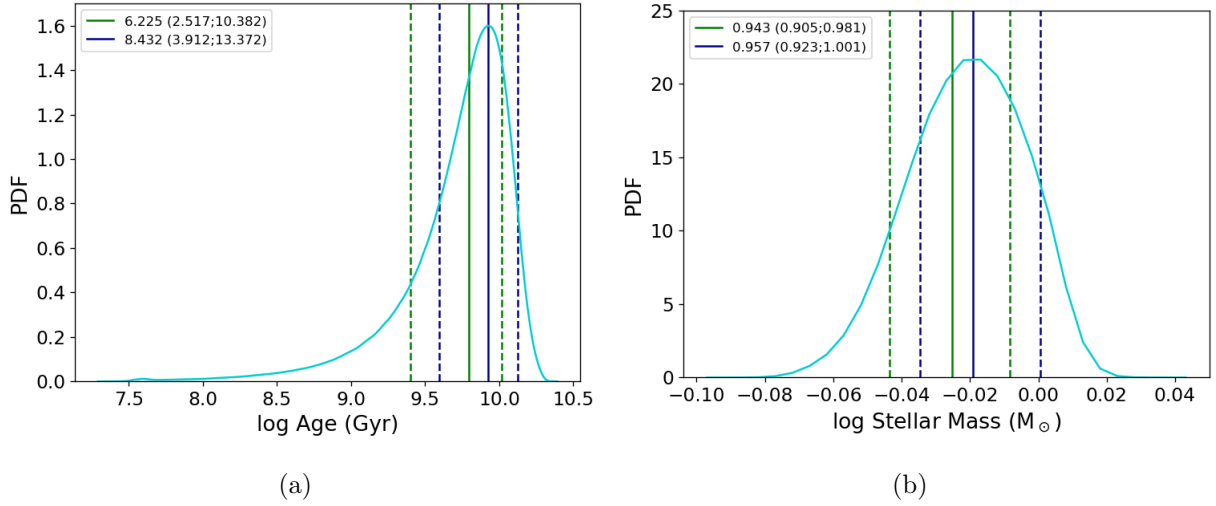


Figure 3.2: PDF of (a) logarithm of age and (b) logarithm of stellar mass obtained with PARAM for 14 Her target presenting single-peaked PDFs. The median and its 68 per cent confidence interval (CI) are represented by green solid lines and green dashed lines, respectively. The mode and its 68 per cent CI are represented in blue solid lines and blue dashed lines, respectively.

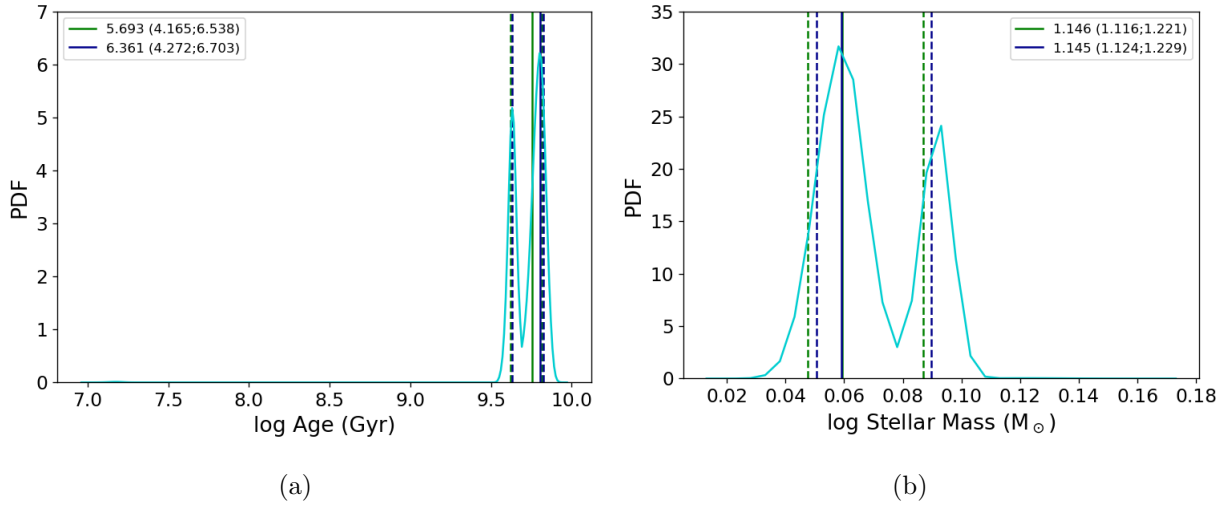


Figure 3.3: PDF of (a) logarithm of age and (b) logarithm of stellar mass obtained with PARAM for EPIC 201295312 target presenting double-peaked PDFs. The median and its 68 per cent CI are represented by green solid lines and green dashed lines, respectively. The mode and its 68 per cent CI are represented in blue solid lines and blue dashed lines, respectively.

and absorb more radiation whose wavelength is similar to their size. The typical size of dust grains is approximately 10^{-7} m (Draine 2004), thus absorbing and scattering more blue light from the objects, making them look redder when observed. Consequently, bluer stars are more affected by extinction and reddening. Therefore, with increasing λ , A_{λ} decreases. Rewriting equation 3.3 for the same star at different wavelengths λ_1 and λ_2 yields

$$(m_{\lambda 1} - m_{\lambda 2}) = (m_{\lambda 1} - m_{\lambda 2})_0 + (A_{\lambda 1} - A_{\lambda 2}). \quad (3.4)$$

The lefthand quantity in equation 3.4 is known as the observed color index, C_{12} , and the first righthand quantity is known as intrinsic color index, C_{12}^0 . The difference between the intrinsic and observed color indices is a measure of reddening known as the color excess, $E_{\lambda 1-\lambda 2}$,

$$E_{\lambda 1-\lambda 2} = A_{\lambda 1} - A_{\lambda 2}. \quad (3.5)$$

Generally, the color excess is written in the UBV system as

$$E_{B-V} = (B - V) - (B - V)_0, \quad (3.6)$$

where B denotes to the blue band and V denotes to the visible band of the spectrum in the UBV system, and are usually referred to the apparent magnitudes m_B and m_V , respectively.

Both the extinction and the color excess are proportional to the column density of dust grains along the line of sight and are related by

$$A_V = 3.1 \times E_{B-V}, \quad (3.7)$$

where A_V is the interstellar extinction at $\lambda = 550$ nm, and the value 3.1 applies to the diffuse ISM (Schultz and Wiemer 1975).

To correct the effects of extinction and reddening at any wavelength, A_λ , the extinction coefficients $k_\lambda = A_\lambda/A_V$ need to be determined first. In broad-band, like *Gaia*, there is a substantial degeneracy between the extinction, effective temperature and spectral energy distribution. Additionally, a bluer star will emit more radiation in the blue-end part of the spectrum, contrary to a redder star, and thus, will be more sensitive to extinction. Therefore, it is important to know the exact passband in which the star emits radiation (Danielski et al. 2018). For that, the extinction coefficients, k_G , k_{BP} and k_{RP} , were determined using the method from Danielski et al. 2018 and Gaia Collaboration et al. 2018. They studied how the extinction coefficients in the *Gaia*-bands vary with the temperature / intrinsic color magnitudes and with total extinction, finding the following relation:

$$k_\lambda = c_1 + c_2(G_{BP} - G_{RP})_0 + c_3(G_{BP} - G_{RP})_0^2 + c_4(G_{BP} - G_{RP})_0^3 + c_5 A_0 + c_6 A_0^2 + c_7(G_{BP} - G_{RP})_0 A_0, \quad (3.8)$$

where $c_1, \dots, c_7$ are the parameters retrieved from Gaia Collaboration et al. 2018, and are presented here in table 3.1. It is important to note that these parameters were calibrated for *Gaia* DR2, while the apparent magnitudes in this work are from *Gaia* DR3, thus the extinction coefficients might be slightly different.

On the other hand, for narrow bands, this degeneracy tends to be negligible leading to a fixed extinction coefficient. This is the case of K_s -band, where the coefficient is simply $k_{K_s} = 0.11675^1$.

¹http://stev.oapd.inaf.it/cgi-bin/cmd_3.7

	c_1	c_2	c_3	c_4	c_5	c_6	c_7
k_G	0.9761	-0.1704	0.0086	0.0011	-0.0438	0.0013	0.0099
k_{BP}	1.1517	-0.0871	-0.0333	0.0173	-0.0230	0.0006	0.0043
k_{RP}	0.6104	-0.0170	-0.0026	-0.0017	-0.0078	0.00005	0.0006

Table 3.1: Parameters from Gaia Collaboration et al. 2018 that were used to derive the *Gaia* extinction coefficients.

In this work, the reddening and its respective uncertainty were retrieved using the SStructuring by Inversion the Local Interstellar Medium (STILISM; Lallement et al. 2014, Lallement et al. 2019), a tridimensional dust map of the local ISM, based on the galactic longitude, l , galactic latitude, b , and distance, d .

The method consists of using absorption measurements for stars distributed in distance and direction, which allow to infer a three-dimensional distribution of the interstellar absorbing matter. These measurements are inverted with Bayesian methods, which enable the building of maps whose spatial resolution depends on the distribution of the stars. Each inverted distribution serves as a prior for the next steps, increasing the spatial resolution progressively. In the last actualization of STILISM (Lallement et al. 2019), they combined *Gaia* DR2 photometric data with 2MASS measurements to derive extinction toward stars that possess accurate photometry and relative uncertainties smaller than 20%. In this work, however, it was used the first instance of STILISM based on *Gaia* DR1 (Lallement et al. 2014), since they provided an online form to their result.

In figure 3.4 is presented an example of a reddening curve and respective uncertainties, provided by STILISM, as a function of distance from the Sun in a specific direction.

3.3 Luminosity and Bolometric Correction

The luminosity, L , is an intrinsic property of the star, corresponding to the total energy emitted per second from the surface. It is associated with the total flux, F , of the star at a distance, d , by the following expression

$$F = \frac{L}{4\pi d^2}. \quad (3.9)$$

Therefore, in order to measure luminosity, it is fundamental to know these two quantities. Whereas the apparent magnitude is a measure of the flux at a given wavelength, F_λ , astronomers needed a way to measure the star's true energy, independent of the distance. The absolute magnitude, M_λ , fulfils this role. It is defined as the magnitude that a star would have if it was located at 10 pc from Earth. From equation 3.3, the absolute magnitude at a given wavelength, M_λ , is

$$M_\lambda = m_\lambda - 5 \log_{10} \left(\frac{d}{10\text{pc}} \right). \quad (3.10)$$

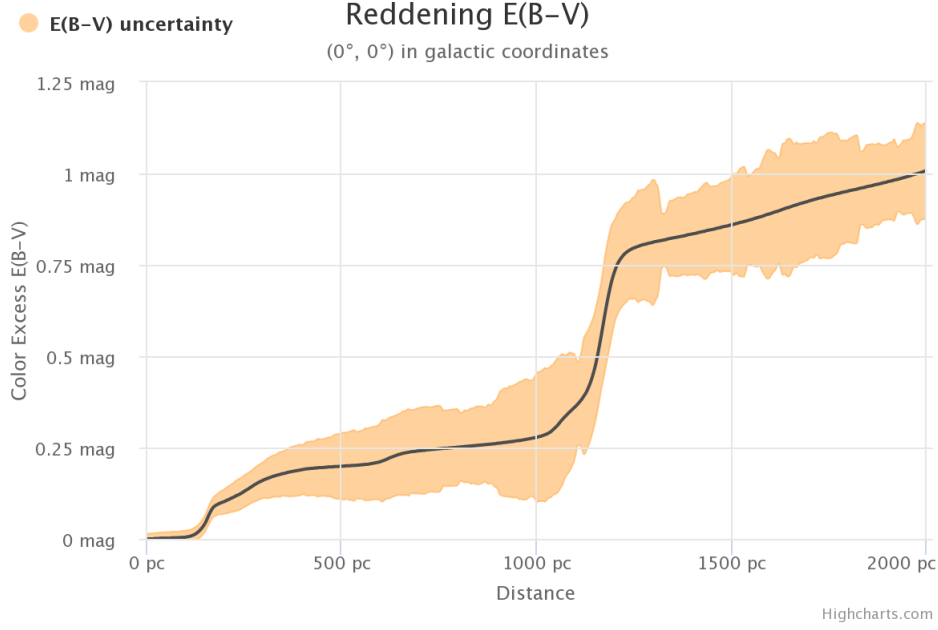


Figure 3.4: STILISM reddening estimates as a function of distance from the Sun in the direction of the galactic centre.

The difference between the apparent intrinsic magnitude and the absolute magnitude is called the distance modulus, DM , and is also a measure of the distance:

$$DM = m_{\lambda} - M_{\lambda} = 5 \log_{10}(d) - 5. \quad (3.11)$$

To get information about the star's total radiation emitted across all wavelengths of the electromagnetic spectrum, and not only in a fixed band, it is essential to correct the absolute magnitudes to bolometric ones, M_{bol} , and in turn, the bolometric luminosity, L_{bol} .

A way to achieved this is by using a bolometric correction for a given band, BC_{λ} , which is simply given by the following expression,

$$BC_{\lambda} = M_{\text{bol}} - M_{\lambda} \Leftrightarrow M_{\text{bol}} = BC_{\lambda} + M_{\lambda}. \quad (3.12)$$

In this work, the bolometric corrections were computed for G and K_s bands through YBC code from Chen et al. 2019, which is also available online². YBC is a database of stellar bolometric corrections for many popular photometric systems, including 2MASS and *Gaia* DR3 filters. The code works by interpolating homogenised stellar spectral libraries in T_{eff} , $\log g$ and $[\text{Fe}/\text{H}]$, giving the convoluted flux in a specific band and converting in a correction to the magnitude. These bolometric corrections can be inferred using equation 3.12. Besides the bolometric correction, YBC also computes the extinction, A_{λ} , in the different passbands from a given E_{B-V} .

The results for bolometric corrections at G -band, BC_G , and at K_s -band, BC_{K_s} , estimated with YBC for each sample are shown in figure 3.5. Since our samples contain mainly FGK stars,

²<http://stev.oapd.inaf.it/YBC/>

and thus, they emit more radiation in the G -band than in K_s -band, the bolometric corrections in the G -band are smaller than the bolometric corrections in the K_s -band, $BC_G < BC_{K_s}$.

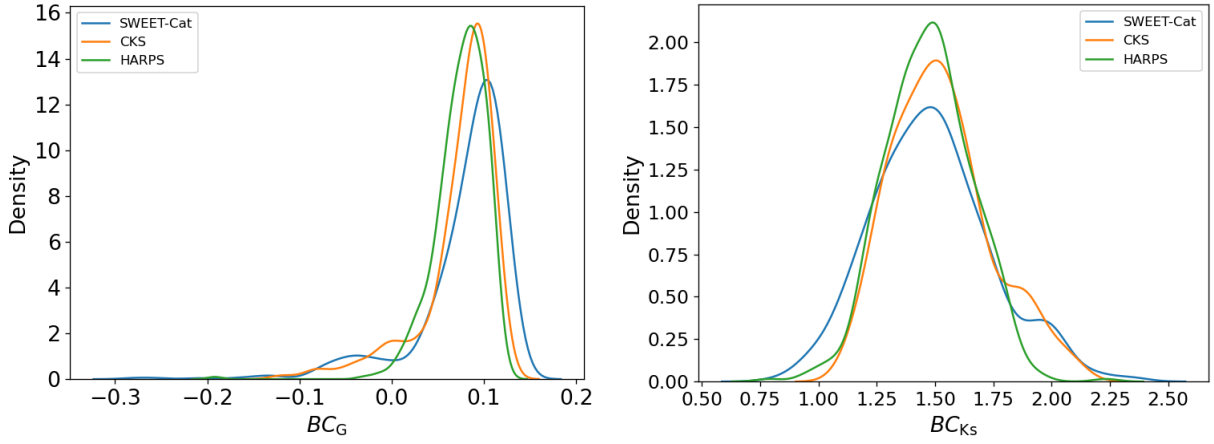


Figure 3.5: The distribution of the bolometric corrections determined with YBC for G -band and for K_s -band, respectively.

After applying the bolometric corrections BC_G and BC_{K_s} to the absolute magnitudes M_G and M_{K_s} , respectively, it is important to note that the estimated bolometric magnitudes, M_{bol}^G and $M_{\text{bol}}^{K_s}$, may differ due to uncertainties in the parameters. Therefore, the luminosities L_{bol}^G and $L_{\text{bol}}^{K_s}$ might also be different, and can be estimated in terms of solar luminosity from equations 3.9 and 3.10 as

$$\frac{L_\lambda}{L_\odot} = 10^{-0.4(M_{\text{bol}} - M_{\text{bol},\odot})}, \quad (3.13)$$

where $M_{\text{bol},\odot} = +4.74$ mag is the absolute bolometric magnitude for the nominal solar luminosity (3.828×10^{26} W) according to Mamajek et al. 2015.

3.4 Stellar Luminosity Estimation

In this Section, the results of L_{bol}^G and $L_{\text{bol}}^{K_s}$ are presented. Since K_s -band is less sensitive to interstellar extinction, it is expected that the results for the luminosity in the same band will be more accurate due to small variation of the extinction, with respect to G -band. On the other hand, the stars in the samples (FGK stars) used in this work emit more radiation in the G -band, and thus, the luminosity results in this band, L_G , are expected to be more precise.

Figure 3.6 shows the difference between the L_{bol}^G and $L_{\text{bol}}^{K_s}$ over the square root of the sum of their uncertainties, δL_{bol}^G and $\delta L_{\text{bol}}^{K_s}$, as a function of distance. When the results are below 1, L_{bol}^G and $L_{\text{bol}}^{K_s}$ are compatible within the uncertainties associated with the measurements, whereas when the results are above 1, it indicates that L_{bol}^G and $L_{\text{bol}}^{K_s}$ are incompatible beyond the expected level of uncertainty. The ratio is larger in the CKS sample, which agrees with the fact that the stars in this sample are located farther away and, thus, are more affected by

extinction. This results in a larger difference between the two luminosity estimates compared to their combined uncertainties.

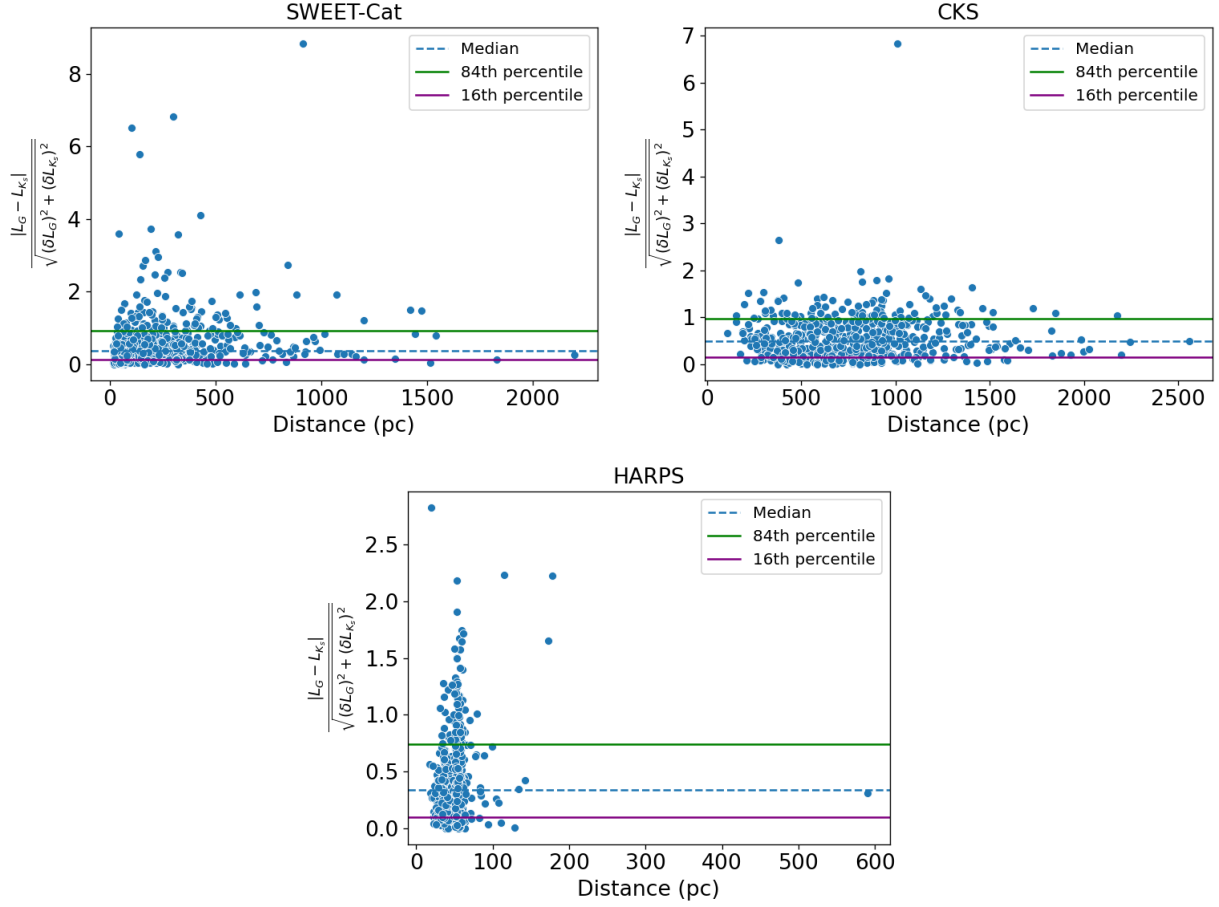


Figure 3.6: Difference between the L_{bol}^G and $L_{\text{bol}}^{K_s}$ over the square root of the sum of their uncertainties, δL_{bol}^G and $\delta L_{\text{bol}}^{K_s}$, as a function of distance, for SWEET-Cat, CKS and HARPS samples. The blue dashed lines represent the median. The green solid lines represent the 84th percentile and the purple solid lines represent the 16th percentile.

For the stellar age estimation, the two luminosities estimated, L_{bol}^G and $L_{\text{bol}}^{K_s}$, were used as inputs in PARAM. Therefore, for each sample, two different ages were inferred, namely τ_G and τ_{K_s} .

3.5 Uncertainties Estimation Method

In the process of estimating the quantities $\{m_\lambda^0, M_\lambda, A_\lambda, E_{B-V}, BC_\lambda, DM, M_{\text{bol}}^\lambda, L_{\text{bol}}^\lambda\}$, a bootstrapping technique was applied to estimate their respective uncertainties. It is important to notice that since some of the properties were estimated through other models and tools rather than simple analytic equations, their uncertainties could only be accounted for through bootstrapping, and so this method was applied to all the properties. Then $N = 1000$ random samples were generated from a normal distribution, where the measured value of each parameter

was used as the mean and its uncertainty was used as the standard deviation. The only exception is E_{B-V} , since it cannot have negative values. Therefore, the values were sampled from a positive normal distribution, between $0.3 < E_{B-V} < 1.5$, corresponding to $0.01 < A_0 < 5$ mag, which is the range of calibration. As a result of this, the uncertainties for each parameter were estimated from the standard deviation of the bootstrapped distribution.

3.6 Best Age Estimation

After stellar ages were estimated through PARAM (Section 3.1.2), it was necessary to address two issues. One issue was to combine in one the two different estimates for the age of each star, τ_G and τ_{K_s} . The other issue was to deal with cases where the estimated age was larger than the age of the Universe, which is currently estimated to be ~ 13.8 Gyr (Planck Collaboration et al. 2020).

To solve these problems, the stars in SWEET-CAT, CKS and HARPS samples, were classified into four groups:

- Stars with $[\tau_G, \tau_{K_s}] > 13.3$ Gyr were assigned with flag **11**.
- Stars with $[\tau_G, \tau_{K_s}] < 13.3$ Gyr were assigned with flag **00**.
- Stars with $\tau_G < 13.3$ Gyr and $\tau_{K_s} > 13.3$ Gyr were assigned with flag **01**.
- Stars with $\tau_G > 13.3$ Gyr and $\tau_{K_s} < 13.3$ Gyr were assigned with flag **10**.

For stars with the flag **00**, random samples were generated from each τ_G and τ_{K_s} PDFs computed by PARAM. Subsequently, the two random samples were combined into a single array, referred to as a joint random choice distribution. The final ages of these stars were determined by calculating the median of the joint random choice distributions, with uncertainties measured as the standard deviation of these distributions. For the sake of consistency, random sample distributions of the PDFs of τ_G and τ_{K_s} were generated for stars with flags **01** and **10**, respectively. Stars flagged as **11** were removed from the sample since their age estimation exceeded the age of the Universe.

The results obtained for stellar ages are presented in the next Chapter.

Note that the age limit is different from the age of the Universe, which is due to the formula related to the galactic birthplace that was applied in Chapter 4.

Chapter 4

Galactic Birthplaces

4.1 Structure of the Galaxy

The Milky Way is a disc galaxy composed of three main components: the bulge, the disc, and the halo (Bland-Hawthorn and Gerhard 2016; Helmi 2020). The anatomy of the Galaxy is illustrated in figure 4.1. Each of these components has distinct features. Not only do their stars have different spatial distributions, but they also differ in age, metallicity, and kinematics, providing information about the several mechanisms involved in the Galaxy’s formation over its lifetime (Helmi 2020).

The bulge is a boxy-shaped region that extends up to ~ 2 kpc from the centre of the Galaxy (Wegg and Gerhard 2013). It contains a higher concentration of stars compared to other regions in the Galaxy, with a total mass of $\sim 1.2 - 1.6 \times 10^{10} M_{\odot}$ (Portail et al. 2015). The bulge is predominantly old, however, studies have shown a mix of stellar populations with a wide range of metal abundances present in this region, which resemble other Galactic components (e.g., Ness et al. 2013). More recently, Lian et al. 2020 proposed three phases for the formation of stars in the galactic bulge: the first consists of an initial starburst, creating metal-poor stars ($[\text{Fe}/\text{H}] < 0$ dex) and α -enhanced stars ($[\text{Mg}/\text{Fe}] > +0.15$ dex), suggesting a rapid formation timescale, followed by a rapid episode of star formation extension, forming metal-rich stars, and finally, a long-lasting phase of secular evolution. Therefore, at least two types of populations can be distinguished in the bulge: a dominant cool, metal-poor, and α -enhanced stars (Population I), and another with a few younger, metal-rich stars (Population II). Most of the galactic bulge is contained within a rotating triaxial structure known as the Galactic bar (Wegg and Gerhard 2013), a component which is expected to extend well beyond the bulge (Portail et al. 2015).

The disc is the flattened component of the Galaxy, located within the galactic plane. The galactic disc is made up of dynamic spiral arms, which are regions of enhanced star formation where gas and dust are highly concentrated. Therefore, it is the place where young stars populate and new stars are constantly formed. Stars in the disc orbit around the centre of the Galaxy in nearly circular orbits. The Galactic disc has two distinct components: a thin and a thick disc.

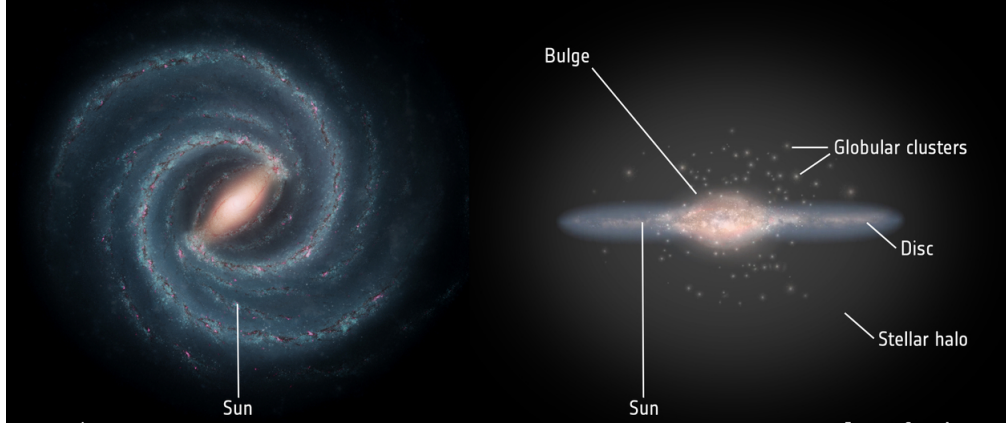


Figure 4.1: Anatomy of the Milky Way. Source: Left: NASA/JPL-Caltech; right: ESA; layout: ESA/ATG medialab.

The presence of the thick disc was discovered by Gilmore and Reid [1983](#). Recently, observational studies have shown that the stellar properties of these two components in fact don't overlap (e.g., Adibekyan et al. [2011](#); Hayden et al. [2015](#)). The thin disc is a site of ongoing stellar formation, with a star formation rate currently estimated at $\sim 1.6 \text{ M}_{\odot} \text{ year}^{-1}$ (Licquia and Newman [2015](#)). Therefore, it contains the majority of the stars in the disc, with a total stellar mass estimated as $\sim 3.5 \times 10^{10} \text{ M}_{\odot}$ (Bland-Hawthorn and Gerhard [2016](#)). The scale height of the thin disc is $\sim 300 \text{ pc}$, and the scale length is $\sim 2.6 \text{ kpc}$ (Bland-Hawthorn and Gerhard [2016](#)).¹ The thick disc is composed of older, metal poorer (Helmi [2020](#)) and kinematically hotter (Bensby et al. [2003](#)) stars than the thin disc. It only contains an estimated stellar mass of $\sim 6 \times 10^9 \text{ M}_{\odot}$. The thick disc is observed to be thicker than the thin disc, with a scale height of $\sim 900 \text{ pc}$ and a horizontal scale length of $\sim 2 \text{ kpc}$ (Bland-Hawthorn and Gerhard [2016](#)).

The halo surrounds the Galactic disk. It is the most extended component of the Galaxy, however, it is centrally concentrated and contains only $\sim 1\%$ of the total stellar mass in the Galaxy. This component reveals the formation history, such as past mergers, of the Galaxy (Helmi [2020](#)). The Galactic halo contains very old and metal-poor stars. These stars show high velocity dispersion and large random motions in comparison to the Galactic disc stars (Helmi [2020](#)).

4.2 How to infer galactic birthplaces?

Grenon ([1972](#), [1989](#)) identified a population of super-metal-rich stars in the solar vicinity. These stars show metallicities that exceed those of the current ISM and of the young stars in the solar vicinity by $\gtrsim 0.25 \text{ dex}$. However, it is not expected that the metallicity of the local ISM would have increased in the past 4 Gyr, suggesting that these stars might have come from the inner disc of the Galaxy.

¹Scale height and scale length are measures of the decrease of a property that falls off exponentially by height and length, respectively. In this case the property is the number of stars.

Sellwood and Binney 2002 showed that stars tend to radially migrate from their birth position in the Galaxy. Radial migration can be explained by two different processes. The principal driver for radial migration is dubbed as *churning*, which occurs in locations where the stars are in co-rotating resonance with the transient spiral arms or bar (Sellwood and Binney 2002), leading to permanent changes in the angular momentum of the stellar orbits and, therefore, changes in their orbital guiding radius (average orbital galactocentric radius), in the sense that stars move from one guiding radius to another while their orbital eccentricities remain the same. The other process is called *blurring* and results from interactions with giant molecular clouds (GMCs; Schönrich and Binney 2009), which scatters away the stars, temporarily changing the eccentricities of their orbits without changing their orbital angular momentum. Additionally, mergers and perturbations from satellite galaxies have also been studied as drivers of radial migration (Quillen et al. 2009).

Stellar migration redistributes stars in the Galactic disc (Lian et al. 2022). Haywood 2008 found high metallicity dispersion in the age-metallicity distribution at the solar neighbourhood and that the dispersion increases with age. Moreover, radial migration erases the kinematic history of the stars, making it challenging to distinguish migrating stars from those born locally. Therefore, trying to infer the original positions of the stars in the Galaxy from their kinematics is almost an impossible task.

Metallicity is a birth property of stars. Stars exhibit metallicities that reflect the metallicity of the ISM at a specific time and position at which they were formed.

Understanding the evolution of ISM abundances in terms of both time and galactocentric radius is the key to inferring the birthplaces of stars (Minchev et al. 2018). This is achieved by comparing the chemical abundance of a star of a particular age (assuming age is equivalent to look-back time) with the chemical composition of the ISM at the time of the star’s formation.

When stars die, part of the chemical elements created in their interiors are returned to the ISM, enriching the metallicity of the ISM over time and, then, making the next generations of newly formed stars more metallic than the previous ones. The production of elements depends on stellar mass (Bovy 2023; Matteucci 2021, and references therein):

- Low and intermediate mass stars ($M_{\star} \sim 0.8\text{--}8\ M_{\odot}$) produce He, N, C, and heavy *s*-process (slow process) elements (e.g., Ba, Y, Sr) in their interiors during the AGB phase. These products are returned into the ISM through stellar winds or super-winds that result in planetary nebulae. These stars end their lives as white dwarfs composed of C and O. However, in the presence of a companion, they may accrete from its mass, become unstable, and then explode as a Type Ia supernova (SN). Heavy elements returned to the ISM by type Ia SN are mostly created in the explosive nucleosynthesis stage.
- Massive stars ($M_{\star} \gtrsim 8\ M_{\odot}$) are able to develop nuclear burning up to the formation of a central nickel-iron core, followed by successive O-, C-, He-, and H-burning shells. During their lives, some of their elements are returned to the ISM through stellar winds; however,

as they evolve, the core cannot support the gravity of the star and collapses. The star explodes as a Type II SNe. These stars produce, in the explosive nucleosynthesis, the bulk of α -elements (e.g., O, Ne, Mg) and some Fe, being the main contributors to the chemical evolution of the ISM.

These processes enrich the ISM on different timescales. As discussed in the previous Chapter, the lifetime of a star decreases with stellar mass. Therefore, stars with $M_{\star} < 0.8 M_{\odot}$ do not contribute to the ISM enrichment since they evolve slowly, surpassing the age of the universe. Low- and intermediate-mass stars produce their elements on a large range of timescales, from 35 Myr to various Gyr. Even massive stars require some tens of millions of years to produce α -elements (Matteucci 2021).

The ISM metallicity gradient of the Milky Way's disc is observed to be negative, meaning that the ISM metallicity decreases with galactocentric radius, r . Some works established that this negative gradient is a result of an inside-out forming Galactic disc (e.g., Matteucci and Francois 1989), which is also supported by observations of older stellar populations being concentrated centrally in the disc (e.g., Bensby et al. 2011).

In this scenario, the star formation timescales increase as a function of the galactocentric radius. More stars are formed per unit of time in the inner disc, leading to a higher enrichment of the ISM, compared to the outer disc, which forms later (Frankel et al. 2019). Stellar migration flattens the ISM metallicity gradient over time, in the sense that older stars located at any radius show a steeper metallicity gradient than do younger stars (Minchev et al. 2018). As older stars have higher velocity dispersion and are more prone to migrate, at high $|z|$ ² is found a slightly positive metallicity gradient (Anders et al. 2017; Minchev et al. 2014), whereby very old and metal-poor stars dominate the inner disc - a consequence of the inside-out disc formation - while younger, metal-rich stars dominate the outer disc - a consequence of disc flaring (Minchev et al. 2018).

4.2.1 Method

In this work, the method developed by Minchev et al. 2018 was implemented to infer the Galactic birthplaces of stars and their exoplanets. This method consists of projecting stars back to their birth position according to their age and $[\text{Fe}/\text{H}]$ estimates (figure 4.2), with no kinematical data required, which makes this semi-empirical and model-independent approach intuitive and easy to interpret. The authors constrained the Galactic ISM metallicity evolution with time and galactocentric radius, $[\text{Fe}/\text{H}]_{\text{ISM}}(t, r)$, using metallicities and ages estimates from the local sample of stars HARPS-GTO (Delgado Mena et al. 2017), relying on the following assumptions:

- The present day ISM metallicity gradient is $-0.07 \text{ dex kpc}^{-1}$;
- The ISM gradient is always negative;

²Distance perpendicular to the Galactic plane.

- The r_{birth} distribution of younger stars needs to peak at the galactic solar radius, $r_{\odot} = 8$ kpc, meaning that these stars are born locally and no migration is expected;
- The r_{birth} distribution of older stars needs to peak successively at smaller formation radii, a consequence of the inside-out formation of the Milky Way's disc and that more migration is expected for these stars;
- ISM metallicity is well mixed, i.e., stars are born with the same metallicity at a fixed time and radius.

They found that the time evolution of the ISM metallicity at the solar radius, $[\text{Fe}/\text{H}]_{\text{ISM}}(r_{\odot})$ and the time evolution of the ISM metallicity gradient, $d[\text{Fe}/\text{H}]_{\text{ISM}}/dr$, were best described by logarithmic functions. At early times, the variation of the slope was $-0.15 \text{ dex kpc}^{-1}$, flattening toward redshift zero to the present day $-0.07 \text{ dex kpc}^{-1}$ (figure 4.3).

In practice, the r_{birth} was inferred from the $[\text{Fe}/\text{H}] - r$ relation for a given age (figure 4.2). Their uncertainties were determined through bootstrapping using the same method described in Section 3.5.

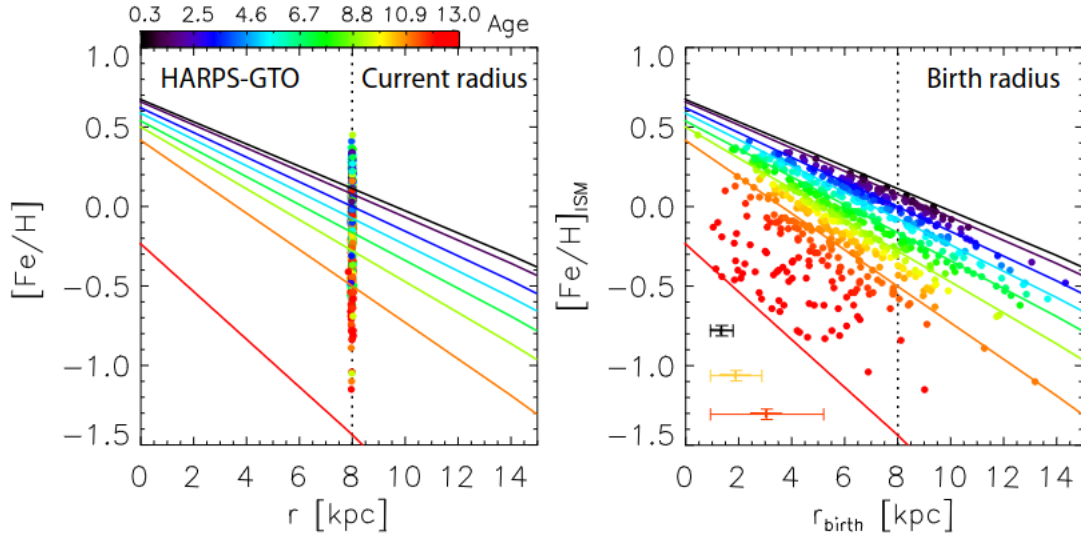


Figure 4.2: Method used by Minchev et al. 2018 to estimate galactic birthplaces. *Left panel:* $[\text{Fe}/\text{H}]$ versus Galactic disc radius, r , showing the currently observed positions of HARPS-GTO stars, with age corresponding to the colour bar. The lines of negative slope represent the best match $[\text{Fe}/\text{H}]$ ISM gradient evolution with time. *Right panel:* $[\text{Fe}/\text{H}]$ versus estimated birth radius, r_{birth} , by projecting stars in radius along the corresponding age gradient.

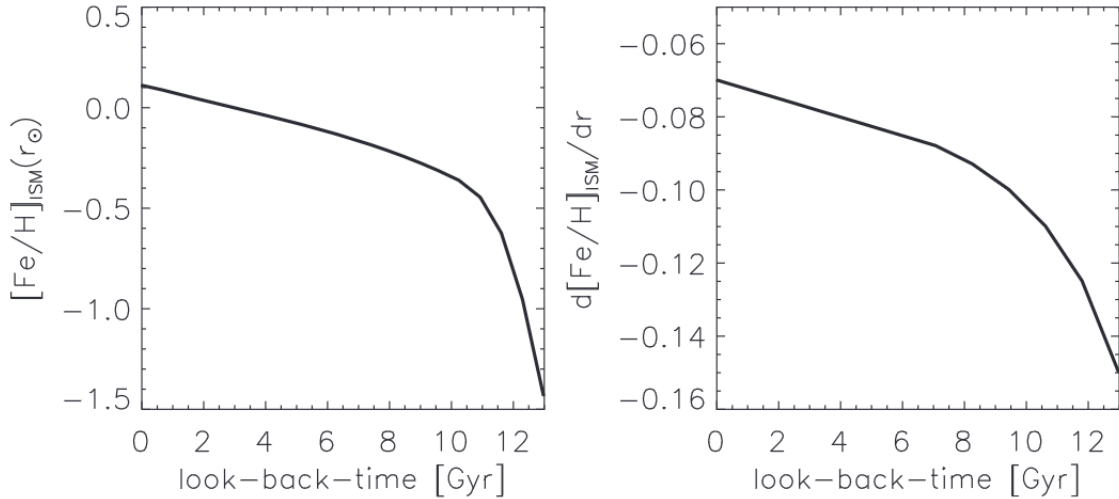


Figure 4.3: Method used by Minchev et al. 2018 to estimate galactic birthplaces. *Left panel*: ISM metallicity variation with time at the solar radius, $[\text{Fe}/\text{H}]_{\text{ISM}}(r_{\odot})$. *Right panel*: ISM metallicity slope variation with time, $d[\text{Fe}/\text{H}]_{\text{ISM}}/dr$.

4.3 Results and Discussion

4.3.1 $[\text{Fe}/\text{H}]$, Stellar ages and Galactic Birth Radii

Figure 4.4 shows the $[\text{Fe}/\text{H}]$, age, and r_{birth} kernel density estimation (KDE) of stars hosting planets (SWEET-Cat and CKS samples) and stars without any detected planets (HARPS sample). KDE (Parzen 1962) is a technique to estimate the probability density function of a random variable (Chen 2017). In this work, the KDE was computed using Seaborn (Waskom 2021).

It is observed that stars hosting planets and stars without planets have different metallicity distributions, with the former being more metallic. In particular, the mean $[\text{Fe}/\text{H}]$ of the SWEET-Cat and CKS samples is 0.12 ± 0.01 dex and 0.06 ± 0.01 dex, respectively, while the mean $[\text{Fe}/\text{H}]$ of the HARPS sample is -0.08 ± 0.01 dex. The errors represent the standard error of the mean, which is calculated as the standard deviation divided by the square root of the sample size.

To quantitatively evaluate the significance of the difference between the three samples, the two-sample Kolmogorov–Smirnov test (KS test; Hodges 1958) was applied, using the `ks_2samp` function from SciPy v1.11.4 (Virtanen et al. 2020) library. The KS test tests the null hypothesis that two samples come from the same parent distribution. The null hypothesis is rejected if the p -value returned from the KS test is below a certain confidence level of 95%, i.e., $p\text{-value} < 0.05$. The KS test shows a p -value of 6.93×10^{-37} for the HARPS and SWEET-Cat samples and a p -value of 4.88×10^{-18} for the HARPS and CKS samples. For SWEET-Cat and CKS samples, the p -value is 2.17×10^{-12} . These results show that the $[\text{Fe}/\text{H}]$ distributions are statistically different. The difference in $[\text{Fe}/\text{H}]$ between SWEET-Cat and CKS samples might be due to the

fact that CKS stars are further away from Earth than SWEET-Cat stars or because of the type of planets these samples host (CKS stars show to host mostly low-mass planets and SWEET-Cat stars show to host mostly high-mass planets).

Different age distributions of stars hosting planets and stars without planets are also observed. The HARPS sample shows a wider range in age than the SWEET-Cat and CKS samples. In particular, the mean age of the HARPS sample is 6.4 ± 0.1 Gyr, being the oldest sample, while the mean age of the SWEET-Cat and CKS samples is 4.5 ± 0.1 Gyr and 5.9 ± 0.1 Gyr, respectively. The KS test shows a p -value of 2.60×10^{-16} for the HARPS and SWEET-Cat samples and a p -value of 6.89×10^{-6} for the HARPS and CKS samples. For the SWEET-Cat and CKS samples, the p -value is 5.09×10^{-22} . These results demonstrate that there is a significant statistical difference in age between the samples.

Analysing the r_{birth} distributions, the stars hosting planets appear to come from smaller galactocentric radii than stars without planets. In particular, the mean r_{birth} for SWEET-Cat and CKS samples is 5.8 ± 0.1 kpc and 5.9 ± 0.1 kpc, whereas the mean r_{birth} for the HARPS sample is 7.2 ± 0.1 kpc. The KS test shows a p -value of 7.79×10^{-15} for the HARPS and SWEET-Cat samples and a p -value of 1.74×10^{-16} for the HARPS and CKS samples. For the SWEET-Cat and CKS samples, the p -value is 0.014. The KS tests show that there is a significant statistical difference in r_{birth} between the samples.

In order to get an insight into the properties of the stars that constitute the samples of this work at a certain r_{birth} , it is shown in figure 4.5 the age-[Fe/H] relation for SWEET-Cat, CKS, and HARPS samples (from left to right panel). The colours represent the r_{birth} in intervals of 3 kpc. It can be seen that the [Fe/H] decreases with r_{birth} , suggesting a negative metallicity gradient, which can be explained by the inside-out disc formation. On the other hand, at a given radius, younger stars are more metal-rich than older stars, which can be explained by the ISM enrichment over time. These results are also found in Minchev et al. 2018 since they used these observational evidences when they constructed their model.

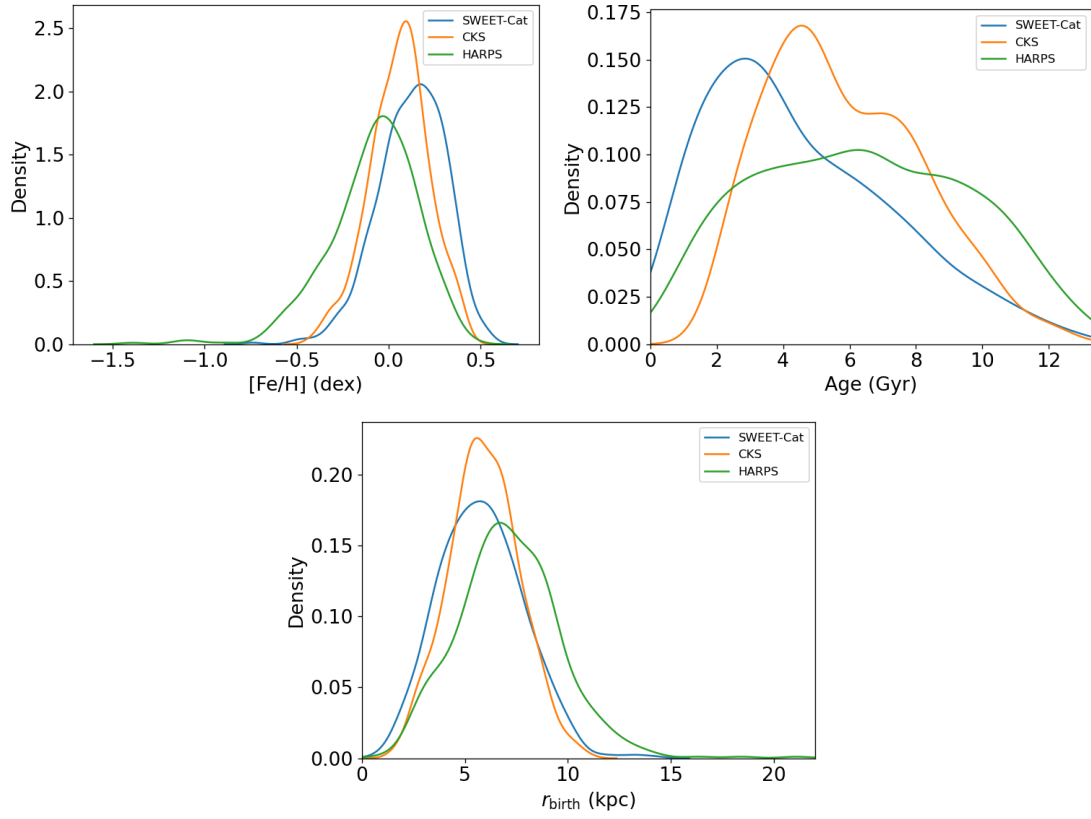


Figure 4.4: KDE of $[\text{Fe}/\text{H}]$, age and r_{birth} distributions for the SWEET-Cat, CKS and HARPS samples.

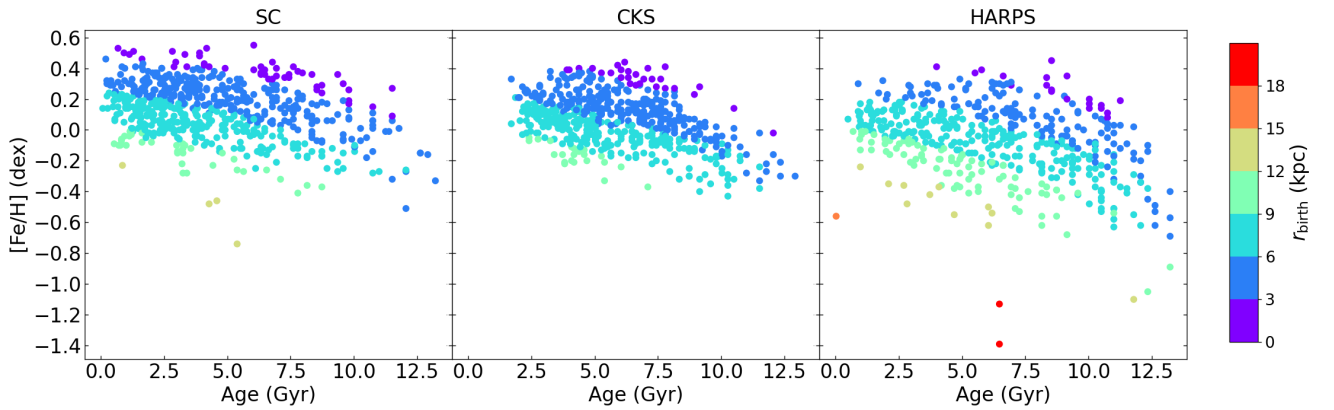


Figure 4.5: Age- $[\text{Fe}/\text{H}]$ relation of SWEET-Cat, CKS and HARPS samples (from left to right). The colours represent the r_{birth} in intervals of 3 kpc.

4.3.2 Exoplanets birthplaces

The planet-hosting star samples (SWEET-Cat and CKS) were divided into two groups according to the planetary mass they host: stars hosting low-mass planets with $M_p \leq 30 M_\oplus$ (hereafter, LMPHs: 84 planetary systems for SWEET-Cat and 38 planetary systems for CKS), and stars hosting high-mass planets with $M_p \geq 50 M_\oplus$ (hereafter, HMPHs: 499 planetary systems for SWEET-Cat and 34 planetary systems for CKS). Notice that different works may have chosen different lower and upper mass limits for high-mass planets (HMPs) and low-mass planets (LMPs). Observations and CA models predicted values around $30 M_\oplus$ for LMPs and values around $50 M_\oplus$ for HMPs (e.g., Mayor et al. 2011; Mordasini et al. 2009). Nevertheless, these values essentially correspond to the observed mass gap presented in mass-period and mass-radius diagrams (Adibekyan 2019). Additionally, it is important to note that multi-planetary systems can appear in both LMPHs and HMPHs groups.

Besides, the maximum mass of each planetary system was selected. The planet-hosting star samples were divided into two groups according to the maximum planetary mass they host, resulting in: stars hosting exclusively low-mass planets with $M_p \leq 30 M_\oplus$ (hereafter, ELMPHs: 60 planetary systems for SWEET-Cat and 28 planetary systems for CKS), and HMPHs.

4.3.2.1 Planetary Mass and [Fe/H]

In the top panel of figure 4.6 is shown the KDE of [Fe/H] distributions for LMPHs and HMPHs. The mean [Fe/H] of LMPHs is 0.06 ± 0.02 dex and 0.09 ± 0.03 dex for the SWEET-Cat and CKS samples, respectively, and increases for HMPHs to 0.14 ± 0.01 dex and 0.15 ± 0.03 dex for the SWEET-Cat and CKS samples, respectively. In the lower panel is shown the KDE of the [Fe/H] distributions for ELMPHs and HMPHs. For ELMPHs, the mean [Fe/H] decreases to 0.04 ± 0.02 dex and 0.05 ± 0.03 dex for the SWEET-Cat and CKS samples, respectively. The KDE of [Fe/H] for the HARPS sample is also shown for comparison in both panels. On average, HARPS stars still remain the least metallic among all the groups.

The KS test p -value results are shown in Table 4.1. For the SWEET-Cat sample, the KS test p -values suggest that for all groups, the metallicity distributions are significantly different. When comparing them to single stars in the HARPS sample, the p -values also suggest that the metallicity distributions are significantly different. For the CKS sample, due to the fact that many planets do not have derived masses (only 64 planet host stars have planetary mass measurements), it is not possible to draw conclusions about this sample, and the p -value may not be a reliable measure of significance in this case.

The giant-planet correlation continues to be present in the results of this work (see discussion in Section 1.2.3). Additionally, [Fe/H] is lower for ELMPHs than for LMPHs but higher than for single stars, which is in accordance with previous works (e.g., Adibekyan 2019). However, contrary to Adibekyan 2019, this work suggests a significant statistical difference between ELMPHs and single stars.

In Figure 4.7 is shown the relation between planetary mass and stellar metallicity in SWEET-Cat and CKS samples. The planets are displayed in two groups (LMPs and HMPs) using different colours, and regression lines are plotted for each group. A green dashed line is plotted, indicating the mean $[\text{Fe}/\text{H}]$ of the HARPS sample for comparison. In the SWEET-Cat sample, it is observed that as the mass of LMPs increases, the stellar metallicity also increases. This is in accordance with the results of Sousa et al. 2019, which showed that the mass of LMPs increases with metallicity and orbital period. Since the increase in metallicity would mean a higher amount of metals in the protoplanetary disc to form planets, and closer to the star, less quantity of material is available, when a planet forms at that small radius, it will be less massive. However, it is important to take into account that the small number of planets with $M_p \lesssim 5 M_\oplus$ can affect the results. On average, HMPs are hosted by high-metallicity stars. However, here it is observed that these planets can be hosted by stars with a wide range of stellar metallicities, which explains the decreasing trend towards very massive planets. In particular, it is observed that very low metallicity stars ($[\text{Fe}/\text{H}] < -0.6$ dex) can host very massive companions. This is the case of BD+202457, which does not host planets but brown dwarfs with masses of $\sim 21 M_J$ and $\sim 13 M_J$. These relations are not so strong for the CKS sample because of its low number of planetary mass measurements.

Therefore, in figure 4.8 is shown the relation between planetary radius and stellar metallicity for planets in the CKS sample. Small-sized planets ($R_p \lesssim 4 R_\oplus$) are observed around stars with a wide range of stellar metallicities. On the contrary, larger planets are found around stars with metallicities approximately above the solar metallicity. However, it is important to take into account the small number of large planets in this sample, which can affect these results. Although the relation between planetary mass and radius is very complex and depends on planet composition, these data support the giant planet-metallicity correlation.

Table 4.1: The results of the Kolmogorov–Smirnov tests comparing different $[\text{Fe}/\text{H}]$ distributions.

	SWEET-Cat	CKS
LMPHs vs HMPHs	0.000	0.612
ELMPHs vs HMPHs	8.97×10^{-6}	0.140
HMPHs vs HARPS	1.73×10^{-38}	1.12×10^{-6}
LMPHs vs HARPS	1.08×10^{-5}	0.000
ELMPHs vs HARPS	0.005	0.048

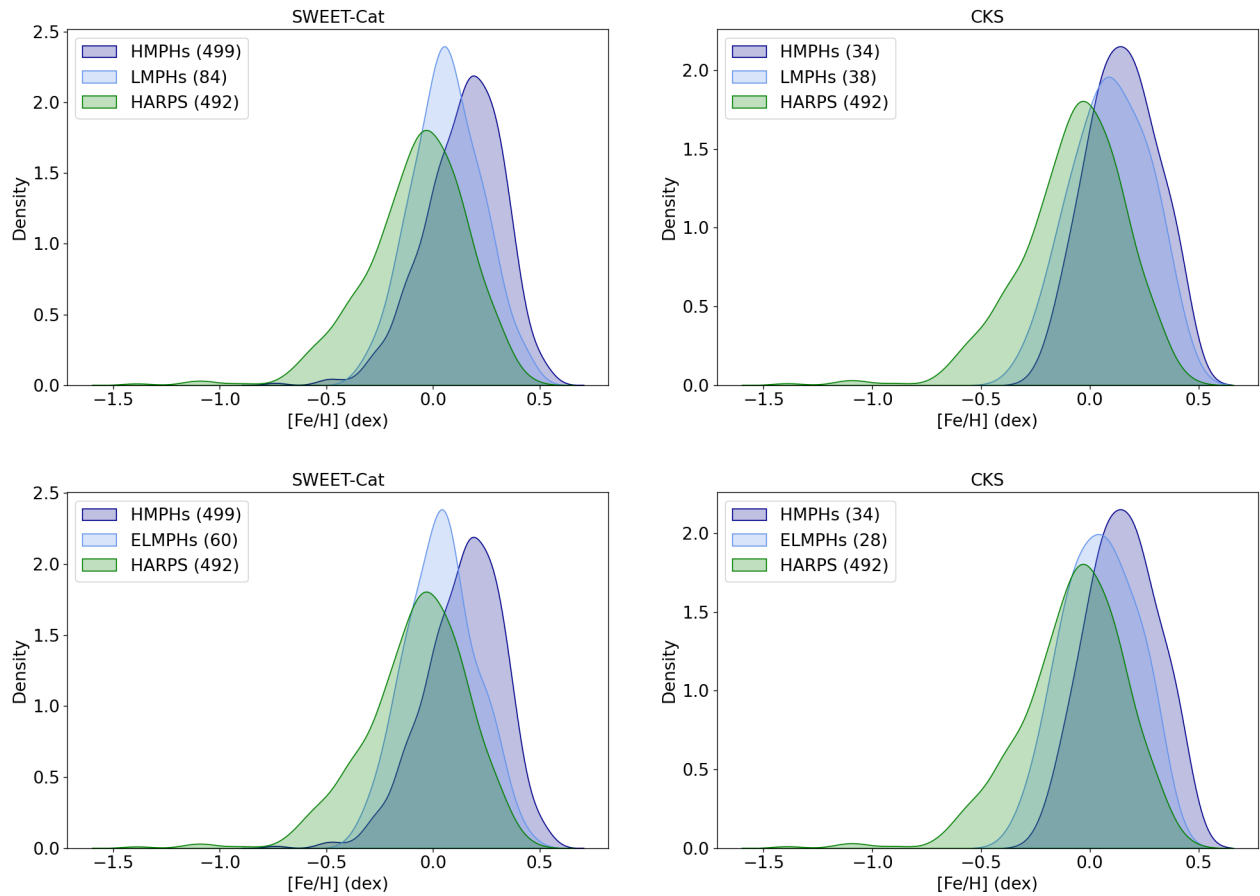


Figure 4.6: *Top panel:* KDE of $[\text{Fe}/\text{H}]$ for high- and low-mass planet host stars (HMPHs and LMPHs) in the SWEET-Cat and CKS samples, and for the HARPS sample. *Lower panel:* KDE of $[\text{Fe}/\text{H}]$ for high-mass planets and stars hosting exclusively low-mass planets (HMPHs and ELMPHs) in the SWEET-Cat and CKS samples, and for the HARPS sample.

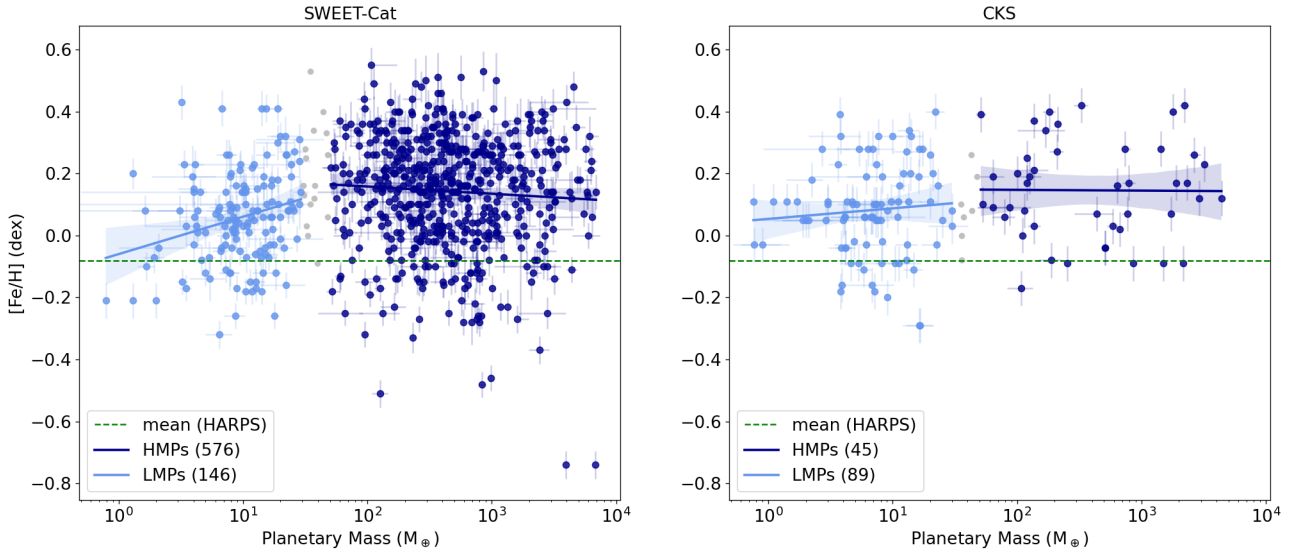


Figure 4.7: $[\text{Fe}/\text{H}]$ as a function of planetary mass for the SWEET-Cat (*left panel*) and CKS (*right panel*) samples. The light blue points represent the low-mass planets (LMPs) and the dark blue points represent the high-mass planets (HMPs). The error bars represent the uncertainties of the parameters for LMPs and HMPs. The regression lines for LMPs and HMPs are plotted using the respective colors. The grey points are the planets with mass between 30 and 50 $M_{\oplus}$. For comparison, the mean $[\text{Fe}/\text{H}]$ of the HARPS sample is represent by the dashed green line.

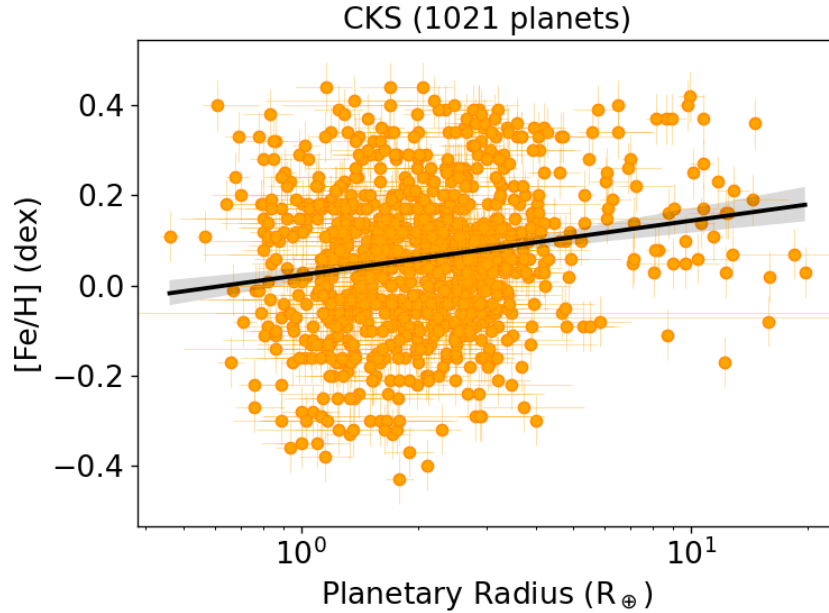


Figure 4.8: $[\text{Fe}/\text{H}]$ as a function of planetary radius for the CKS sample. The error bars represent the uncertainties of the parameters. The black solid line represents the linear regression.

4.3.2.2 Planetary Mass and Stellar Age

In the top panel of figure 4.9 is shown the KDE of age distributions for LMPHs and HMPHs. The mean age of LMPHs is 5.8 ± 0.3 Gyr and 6.1 ± 0.3 Gyr for the SWEET-Cat and CKS samples, respectively, and decreases for HMPHs to 4.3 ± 0.1 Gyr and 5.4 ± 0.4 Gyr for the SWEET-Cat and CKS samples, respectively. In the lower panel is shown the KDE of age distributions of ELMPHs and HMPHs. For ELMPHs, the mean age increases to 6.2 ± 0.4 Gyr and 6.5 ± 0.4 Gyr for the SWEET-Cat and CKS samples, respectively. The KDE of age for the HARPS sample is also shown for comparison in both panels. On average, HARPS stars still remain the oldest among all the samples.

The KS test p -value results are shown in table 4.2. For the SWEET-Cat sample, the KS test p -values suggest that for HMPHs, LMPHs, and ELMPHs, the age distributions are significantly different. When comparing the distributions of planet host stars groups to the distribution of single stars, the p -value suggests that HMPHs and HARPS stars do not come from the same parent distribution, whereas a p -value of 0.099 for LMPHs and HARPS stars and a p -value of 0.631 for ELMPHs and HARPS stars indicates that these distributions may come from the same parent distribution. For the CKS sample, the fact that many planets do not have derived masses (only 64 planet host stars have planetary mass measurements), it is not possible to draw conclusions about this sample, and the p -value may not be a reliable measure of significance in this case.

Figure 4.10 shows the relation between planetary mass and stellar age in SWEET-Cat and CKS samples. In the SWEET-Cat sample, it is observed that LMPs are hosted by stars with a wide stellar age range. On the other hand, HMPs are more concentrated towards younger stars as the planetary mass increases. This is in accordance with ISM enrichment over time. Younger stars are more metallic, favouring the formation of HMPs, as predicted by CA models. On the other hand, young stars are active, increasing the difficulty of detecting LMPs around these stars (e.g., Faria et al. 2016; Santos et al. 2014; Tal-Or et al. 2018).

As the CKS sample has a low number of planetary mass measurements, in figure 4.11 is shown the relation between planetary radius and stellar age of the CKS sample. It is observed that small-sized planets ($R_p \lesssim 4 R_\oplus$) are hosted by stars with a wide range in age, whereas large planets are more concentrated towards younger stars. Again, it is important to take into account the small number of large planets in this sample, which can affect these results.

Table 4.2: The results of the Kolmogorov–Smirnov tests comparing different age distributions.

	SWEET-Cat	CKS
LMPHs vs HMPHs	1.16×10^{-5}	0.310
ELMPHs vs HMPHs	5.42×10^{-6}	0.041
HMPHs vs HARPS	3.20×10^{-20}	0.027
LMPHs vs HARPS	0.099	0.049
ELMPHs vs HARPS	0.631	0.156

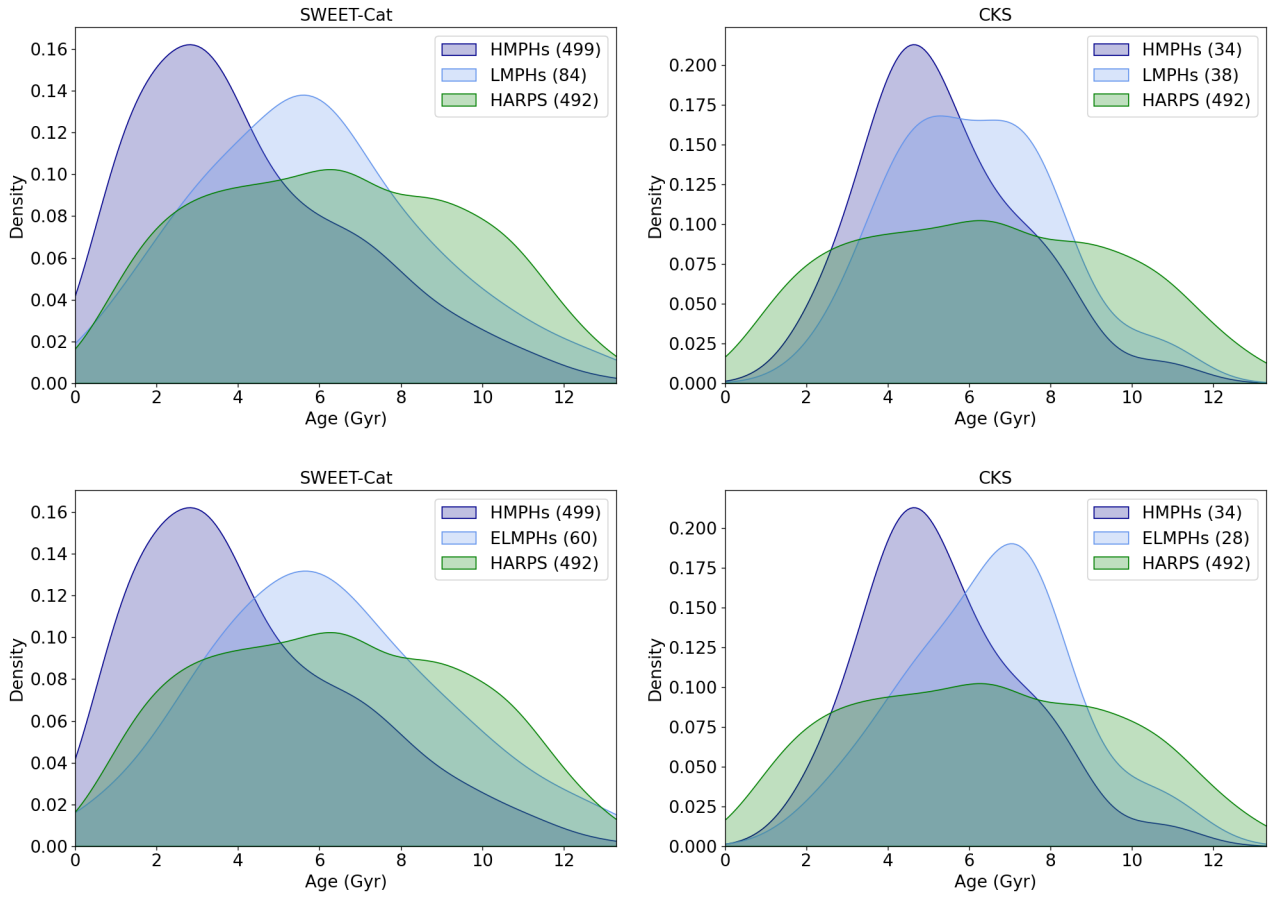


Figure 4.9: *Top panel:* KDE of age for high- and low-mass planet host stars (HMPHs and LMPHs) in the SWEET-Cat and CKS samples, and for the HARPS sample. *Lower panel:* KDE of age for high-mass planets and stars hosting exclusively low-mass planets (HMPHs and ELMPHs) in the SWEET-Cat and CKS samples, and for the HARPS sample.

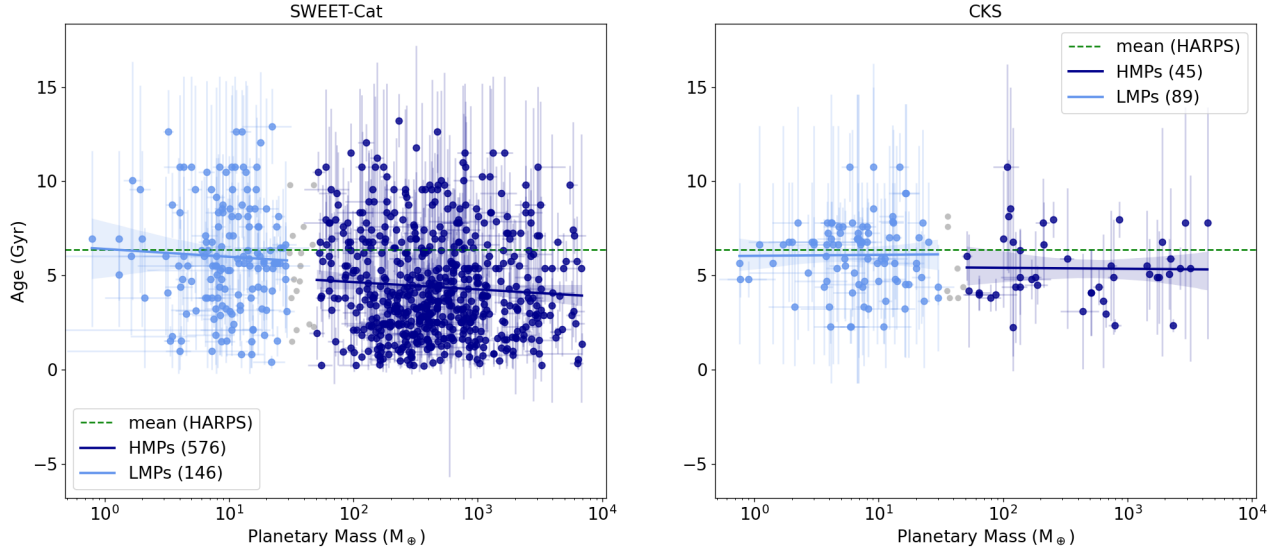


Figure 4.10: Age as a function of planetary mass for the SWEET-Cat (*left panel*) and CKS (*right panel*) samples. The light blue points represent the low-mass planets (LMPs) and the dark blue points represent the high-mass planets (HMPs). The error bars represent the uncertainties of the parameters for LMPs and HMPs. The regression lines for LMPs and HMPs are plotted using the respective colors. The grey points are the planets with mass between 30 and 50 $M_{\oplus}$. For comparison, the mean age of the HARPS sample is represented by the dashed green line.

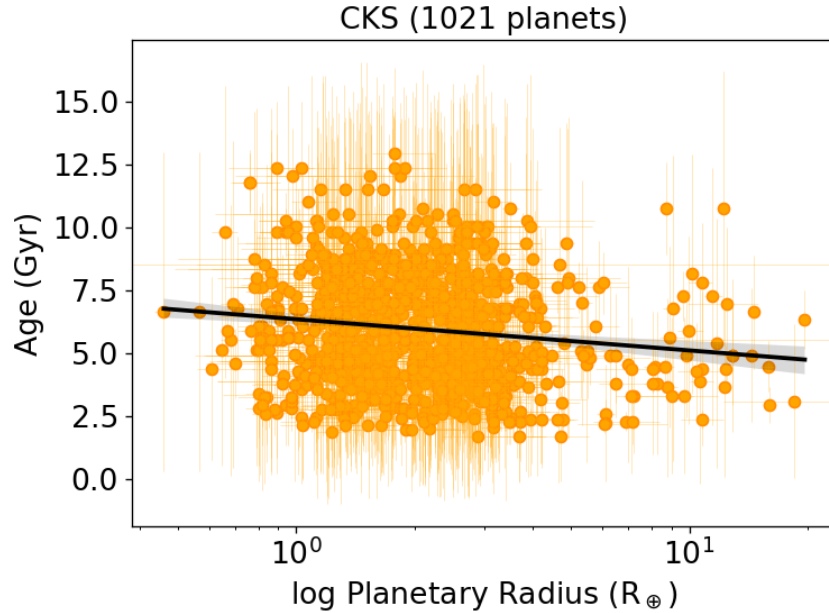


Figure 4.11: Age as a function of planetary radius for the CKS sample. The error bars represent the uncertainties of the parameters. The black solid line represents the linear regression.

4.3.2.3 Planetary Mass and Galactic birthplaces

In the top panel of figure 4.12 is shown the KDE of r_{birth} distributions of LMPHs and HMPHs. The mean r_{birth} of LMPHs is 5.9 ± 0.2 kpc and 5.5 ± 0.3 kpc for the SWEET-Cat and CKS samples, respectively, and slightly decreases for HMPHs, to 5.8 ± 0.1 kpc and 5.3 ± 0.3 kpc for the SWEET-Cat and CKS samples, respectively. In the lower panel is shown the KDE of r_{birth} distributions of ELMPHs and HMPHs. For ELMPHs, the mean r_{birth} increases to 6.1 ± 0.2 kpc and 5.8 ± 0.3 kpc for the SWEET-Cat and CKS samples, respectively. The KDE of r_{birth} for the HARPS sample is also shown for comparison in both panels.

The KS test p -value results are shown in Table 4.3. For the SWEET-Cat sample, the KS test p -values suggest that for HMPHs, LMPHs, and ELMPHs, the r_{birth} distributions come from the same parent distribution. However, when comparing these groups to the HARPS stars, the p -values suggest that these distributions do not come from the same parent distribution. For the CKS sample, the fact that many planets do not have derived masses (only 64 planet host stars have planetary mass measurements), it is not possible to draw conclusions about this sample, and the p -value may not be a reliable measure of significance in this case.

These results indicate that the dependence of the formation of HMPHs, LMPHs, and ELMPHs on r_{birth} is nearly the same, for which HMPHs demonstrate to come from slightly smaller galactocentric radii than LMPHs and ELMPHs. On average, HARPS stars show the largest r_{birth} among all the groups. This can be explained by the fact that, at a small galactocentric radius, the ISM is more metallic, favouring the formation of planets.

The relation between planetary mass and r_{birth} in SWEET-Cat and CKS samples is shown in figure 4.13. Analyzing this relation in the SWEET-Cat sample, it is observed that for LMPs, the r_{birth} appears to decrease with increasing planetary mass. This is in accordance with the fact that metallicity increases with planetary masses for these planets (figure 4.7), increasing the efficiency of the formation of planets and more massive planets. On the other hand, planets with $M_p \lesssim 5 M_{\oplus}$ are very hard to detect, and this can affect the results. For HMPs, the r_{birth} seems to increase slightly with planetary mass. In fact, it is observed that some of these planetary systems were formed at very large galactocentric radii. This is the case of BD+202457. This agrees with the negative ISM metallicity gradient, where at large galactocentric radii, the metallicity of the ISM is very low, reflecting on the metallicity of the star. In general, the trend observed for HMPs is also in agreement with the trend observed in figure 4.7 for HMPs.

In figure 4.14 is shown the relation between planetary radius and r_{birth} in the CKS sample. Small-sized planets appear to have formed at any r_{birth} . In contrast, larger planets appear to have formed in a slightly smaller range of galactocentric radius. Again, it is important to note that the small sample statistic of large planets can affect the results.

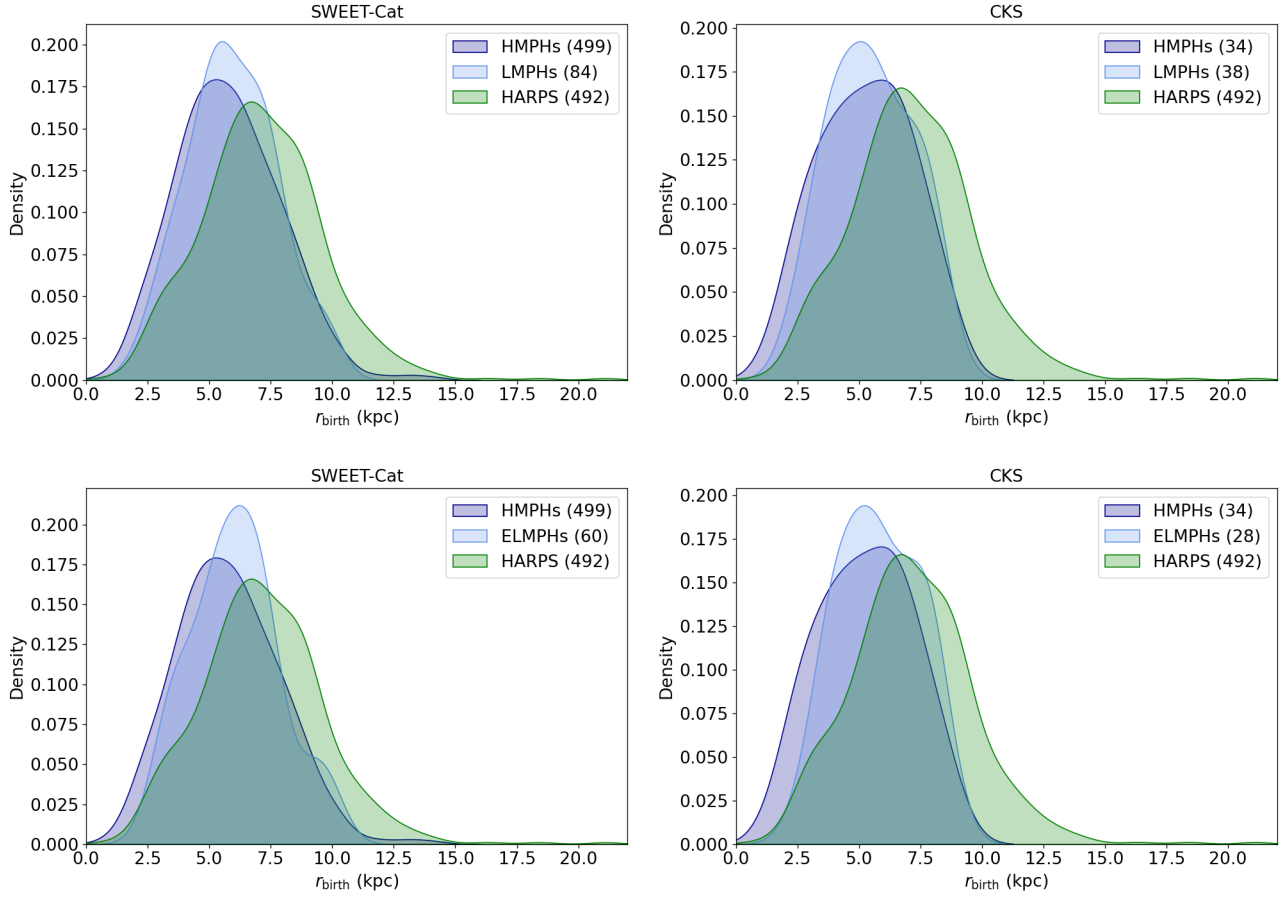


Figure 4.12: *Top panel:* KDE of r_{birth} for high- and low-mass planet host stars (HMPHs and LMPHs) in the SWEET-Cat and CKS samples, and for the HARPS sample. *Lower panel:* KDE of r_{birth} for high-mass planets and stars hosting exclusively low-mass planets (HMPHs and ELMPHs) in the SWEET-Cat and CKS samples, and for the HARPS sample.

Table 4.3: The results of the Kolmogorov–Smirnov tests comparing different r_{birth} distributions.

	SWEET-Cat	CKS
LMPHs vs HMPHs	0.358	0.973
ELMPHs vs HMPHs	0.350	0.496
HMPHs vs HARPS	1.08×10^{-14}	0.001
LMPHs vs HARPS	7.24×10^{-5}	0.000
ELMPHs vs HARPS	0.001	0.012

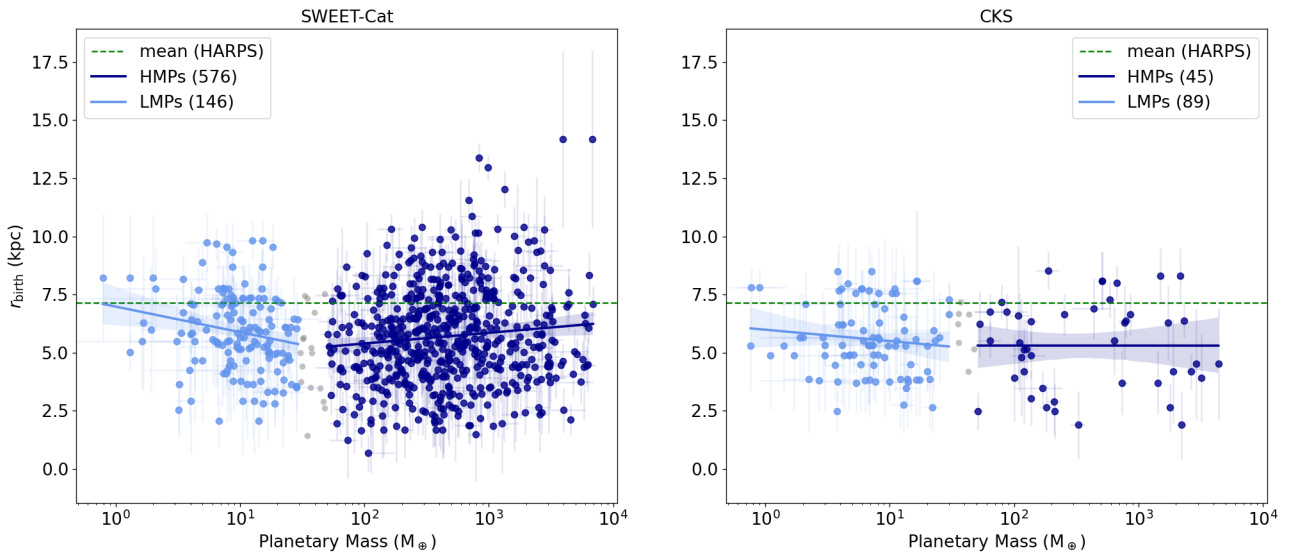


Figure 4.13: r_{birth} as a function of planetary mass for the SWEET-Cat (*left panel*) and CKS (*right panel*) samples. The light blue points represent the low-mass planets (LMPs) and the dark blue points represent the high-mass planets (HMPs). The error bars represent the uncertainties of the parameters for LMPs and HMPs. The regression lines for LMPs and HMPs are plotted using the respective colors. The grey points are the planets with mass between 30 and 50 $M_{\oplus}$. For comparison, the mean r_{birth} of the HARPS sample is represent by the dashed green line.

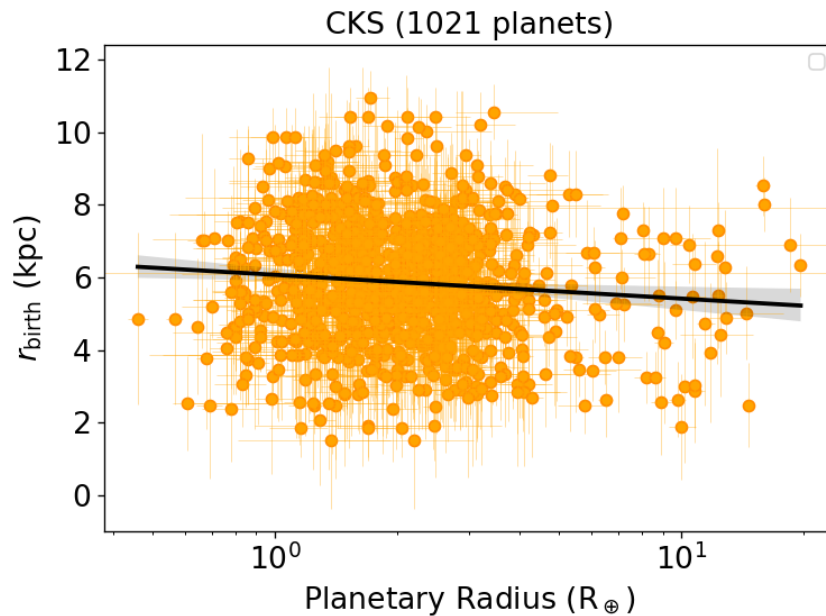


Figure 4.14: r_{birth} as a function of planetary radius for the CKS sample. The error bars represent the uncertainties of the parameters. The black solid line represents the linear regression.

4.3.3 Frequency of planet host stars as a function of stellar properties

In this Section is provided an analysis of the relative frequency of stars hosting planets as a function of $[\text{Fe}/\text{H}]$, age, and r_{birth} .

The relative frequency of stars hosting planets was computed as

$$\text{Relative Frequency} = \frac{\text{Number of stars hosting planets}}{\text{Total number of stars}}, \quad (4.1)$$

where the number of stars hosting planets correspond to the ELMPHs and HMPHs groups in the SWEET-Cat sample, and the total number of stars correspond to the number of stars hosting planets plus the number of stars without detected planets in the HARPS sample. Stars from the CKS sample did not take part in this analysis since the number of stars with planetary mass measurements is small. However, it is important to take into account that this method to calculate the frequency of stars with planets is not the correct one. In fact, the number of stars with planets and stars without planets should be taken from a volume-limited sample whose observations have been monitored over time. Therefore, these numbers do not represent the true planetary frequency. Nevertheless, the observed trends should reflect the true dependencies of the stars hosting planets on $[\text{Fe}/\text{H}]$, age, and r_{birth} .

The upper and lower uncertainties of the relative frequency were computed using a binomial distribution and correspond to the confidence interval level of 68%.

In the left panel of figure 4.15 is shown the number of ELMPHs, HMPHs, and stars without detected planets (HARPS) as a function of $[\text{Fe}/\text{H}]$. The data points represent the number of stars in a bin width of 0.2 dex. The results show again that stars hosting planets are more metallic than stars without detected planets. However, it is also observed that stars with higher metallicity preferentially form HMPs rather than none. In the right panel of this figure is shown the relative frequency of ELMPHs and HMPHs with $[\text{Fe}/\text{H}]$. The relative frequency of ELMPHs and HMPHs can also be interpreted as the *formation efficiency* of LMPs and HMPs, respectively. It is observed that the formation efficiency of both groups of planets increases with stellar metallicity. This relation is more steep for HMPs than for LMPs; however, a slight dependence of the latter is shown towards high metallicities, $[\text{Fe}/\text{H}] > +0.3$. Matsumura et al. 2017 suggested that the star metallicity may have a slight impact on the formation efficiency of LMPs. In their model, a high number of LMPs can be formed, but the majority leave their planetary systems due to dynamical instabilities.

In the left panel of figure 4.16 is shown the number of ELMPHs, HMPHs, and stars without detected planets (HARPS) as a function of age. The data points represent the number of stars in a bin width of 2 Gyr. The number of HMPHs is very high around ages < 3 Gyr and then decreases steeply with age. On the other hand, the number of ELMPHs seems to be constant with age. The number of stars without planets increases with age towards ~ 7 Gyr, but it is still lower than HMPHS for ages < 7 Gyr. It then decreases with age, being higher than the number of HMPHs. Analysing the relative frequency of ELMPHs and HMPHs with age (right panel), it is observed that the formation efficiency of LMPs increases slightly towards ~ 5 Gyr and then

decreases again until 11 Gyr. However, this result can be sensitive to the fact that younger stars are very active, making the detection of these planets very difficult, so this may not portray the reality of the formation efficiency of these planets. For ages > 11 Gyr, the formation efficiency of these planets shows an increase, but this is due to the lower number of ELMPHs and HARPS stars with these ages. The formation efficiency of HMPs steeply decreases with age. Younger stars appear to harbour a significant number of HMPs. This is in accordance with the fact that these stars have high metallicities, as seen in figure 4.5, favouring the formation of these planets predicted by CA models.

In the left panel of figure 4.17 is shown the number of ELMPHs, HMPHs, and stars without detected planets (HARPS) as a function of r_{birth} . The data points represent the number of stars in a bin width of 2 kpc. In this panel, the same results as those discussed in the previous section are observed: ELMPHs and HMPHs have smaller r_{birth} than HARPS stars. In the right panel, the relative frequency of ELMPHs and HMPHs is plotted. The relative frequency of these stars decreases with increasing galactocentric radius. The formation efficiency of HMPs is very high for $r_{\text{birth}} \sim 1$ kpc, decreasing steeply between $1 \text{ kpc} < r_{\text{birth}} < 3 \text{ kpc}$. Between $3 \text{ kpc} < r_{\text{birth}} < 5 \text{ kpc}$, it shows to be constant and decreases steeply again towards larger r_{birth} . The formation efficiency of LMPs is also observed to be higher towards smaller r_{birth} , however, it shows to decrease gradually towards larger r_{birth} . These results are in agreement with the fact that in the inner disc, the metallicity is higher, favouring the formation of planets, especially HMPs. For $r_{\text{birth}} > 11 \text{ kpc}$, the formation efficiency shows an increase for both groups. However, this behaviour can be explained by the fact that at this larger r_{birth} , the number of hosts and non-hosts is very small.

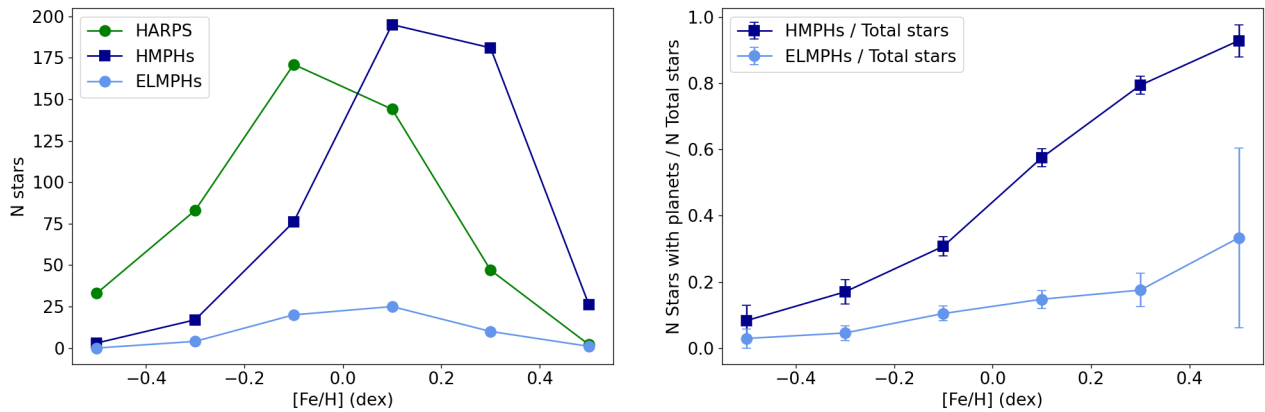


Figure 4.15: *Left*: Number of HMPHs, ELMPHs, and stars without planets (HARPS) as a function of $[\text{Fe}/\text{H}]$. *Right*: Relative frequency of HMPHs and ELMPHs as a function of $[\text{Fe}/\text{H}]$.

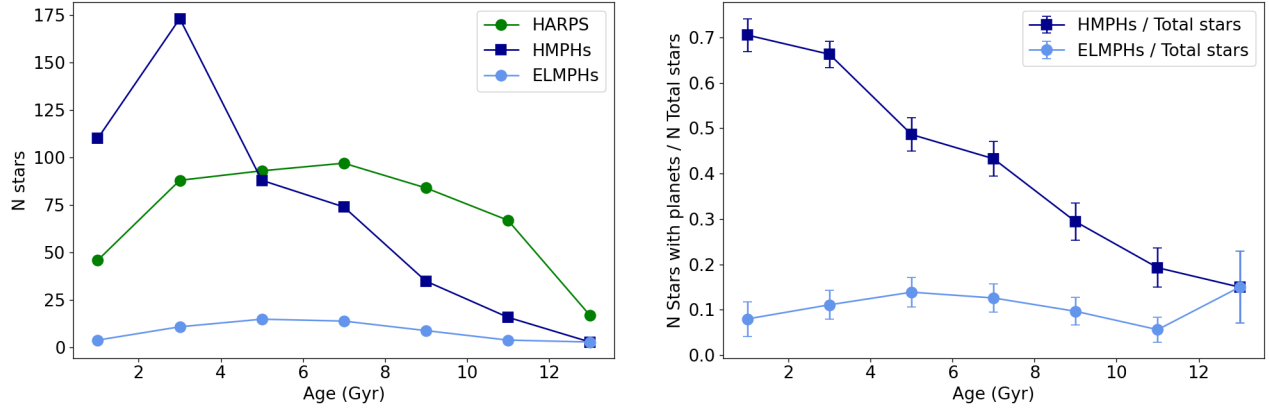


Figure 4.16: *Left*: Number of HMPHs, ELMPHs, and stars without planets (HARPS) as a function of stellar age. *Right*: Relative frequency of HMPHs and ELMPHs as a function of stellar age.

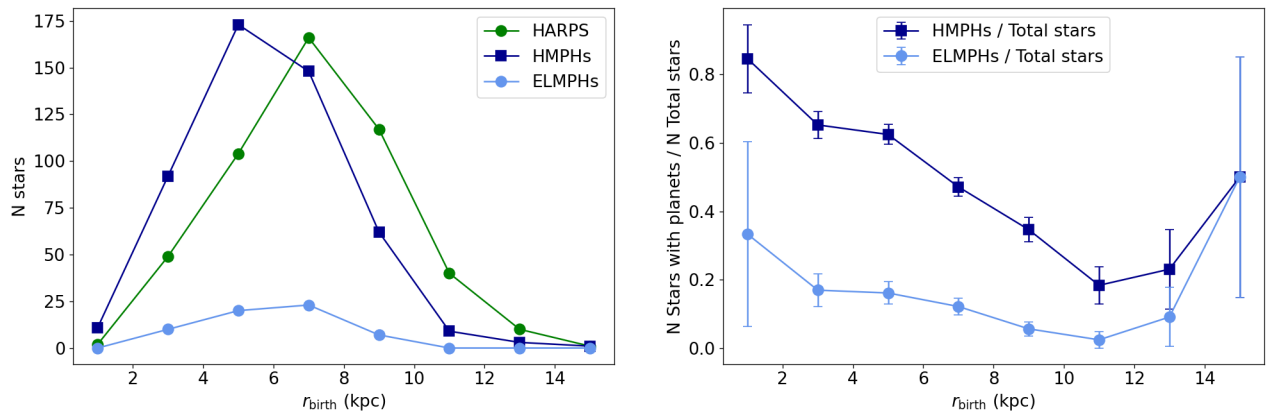


Figure 4.17: *Left*: Number of HMPHs, ELMPHs, and stars without planets (HARPS) as a function of r_{birth} . *Right*: Relative frequency of HMPHs and ELMPHs as a function of r_{birth} .

To get a better insight of these results and how the r_{birth} of stars hosting planets changes over time, the frequency of stars hosting planets as a function of r_{birth} for different stellar age ranges is provided in the figure 4.18. This figure provides the same as figure 4.17 but for different stellar age ranges.

Starting for stars with ages above 8 Gyr, in the left panel of figure 4.18a it is observed that the number of HMPs (54) and ELMPs (16) is significantly lower compared to stars without detected planets (168). Additionally, the stars hosting planets appear to form at a lower galactocentric radius than stars without planets. In particular, the mean r_{birth} is 4.7 ± 0.2 kpc for HMPs, 5.2 ± 0.3 kpc for ELMPs, and 6.2 ± 0.2 kpc for stars without planets. It is observed that older stars almost do not harbour any planets at large galactocentric radii, $r_{\text{birth}} > 9$ kpc. In the right panel of this figure, it is shown that the relative frequency of ELMPs and HMPs decreases with r_{birth} . The formation efficiency of both LMPs and HMPs decreases steeply for $r_{\text{birth}} < 3$ kpc. Between $3 \text{ kpc} < r_{\text{birth}} < 5 \text{ kpc}$, it appears constant and decreases again steeply for HMPs and gradually for LMPs until $r_{\text{birth}} \sim 9$ kpc. For larger galactocentric radii, the formation efficiency of planets appears to increase again very steeply. However, it is important to note that for these large galactocentric radii, the number of stars with and without planets is very low. This matches the fact that, at early times, the metallicity of the ISM was very low compared to what is observed today, which limited the formation of planets, and, in turn, only single stars could form. Additionally, the metallicity gradient was very steep, and the metallicity was high at small galactocentric radii compared to large radii, in turn favouring the formation of planets at smaller radii.

For stars with ages between 4 and 8 Gyr, in the left panel of figure 4.18b it is shown that the number of HMPs (162) increases significantly, being higher for $r_{\text{birth}} < 6$ kpc than stars without planets, and then lower for larger r_{birth} . Stars without planets (190) still dominate at these ages, principally for $r_{\text{birth}} > 6$ kpc. Additionally, the formation of these stars increases at $r_{\text{birth}} \sim 11$ kpc, compared to early times. This means that at this time and radius, the ISM is sufficiently rich to form more single stars than before. The number of ELMPs (29) increases gradually; however, the difference is not that significant in comparison to the previous results. Furthermore, it is observed that, for these ages, the formation of stars is shifted towards larger galactocentric radii. This shift is higher for stars without planets, reaching a mean of 7.4 ± 0.2 kpc, and is more gradual for ELMPs and HMPs, reaching a mean of 5.9 ± 0.3 kpc and 5.4 ± 0.2 kpc, respectively. In the right panel of this figure, it is shown that the relative frequency of both ELMPs and HMPs decreases with galactocentric radii, being steeper for HMPs until $r_{\text{birth}} \sim 11$ kpc. However, it is more gradual than for ages above 8 Gyr. For larger galactocentric radii, it is important to take into account that the number of stars in all groups is very small, which explains the sudden increase in the frequency of stars hosting planets. In general, the formation efficiency of HMPs increases with time, whereas the formation efficiency of LMPs is at nearly the same value as before. This is in agreement with the fact that the ISM metallicity, between 4 and 8 Gyr ago, evolved sufficiently to be able to form more HMPs.

For stars with ages below 4 Gyr, in the left panel of figure 4.18c is shown that the number

of HMPHs (283) increases significantly in comparison with stars without planets (134), which shows a decrease, and only at large galactocentric radii is it slightly higher than HMPHs. The number of ELMPHs (15) decreases slightly. It is observed that the formation of stars has also shifted to a larger r_{birth} , particularly, to 6.2 ± 0.1 kpc for HMPHs, to 7.2 ± 0.4 for ELMPHs, and to 8.1 ± 0.1 for stars without planets. In the recent 4 Gyr, HMPHs appear to form in a wider r_{birth} range, contrary to stars without planets, which appear to form in a slightly narrower r_{birth} than before. In the right panel of this figure, it is shown that the relative frequency of both ELMPHs and HMPHs decreases with r_{birth} . However, in comparison to ages above 4 Gyr, the formation efficiency of HMPHs shows an increase at any galactocentric radius. This can be explained by the enrichment and flattening of the ISM metallicity gradient in the recent Gyr. The formation efficiency of LMPs appears to increase slightly towards small r_{birth} in comparison to ages above 4 Gyr, and then decreases and becomes nearly constant for larger r_{birth} . Again, it is seen an increase in relative frequency at larger r_{birth} , for which the reason must be the same as discussed previously. Furthermore, the metallicity increases sufficiently in the recent years, which favours the formation of HMPs and limits the formation of stars without planets, and therefore, the latter can only form at large r_{birth} , where the metallicity is low enough. Regarding LMPs, the number of these planets appears to vary in galactocentric radii with time, but their formation efficiency appears to be nearly constant with time. However, it is important to take into account that the low sensitivity to detect these planets can constrain a lot the results.

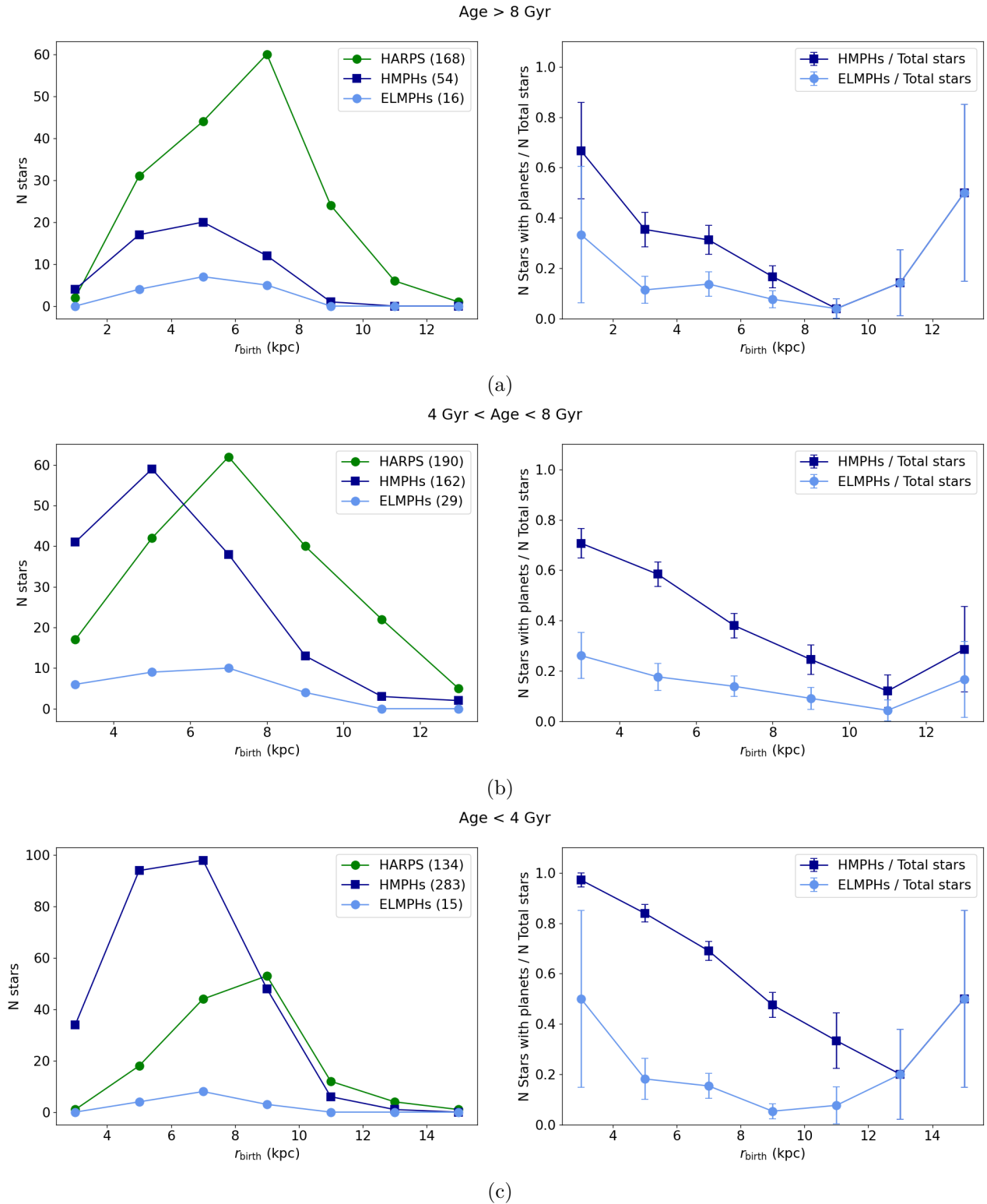


Figure 4.18: *Left panel*: Number of HMPHs, ELMPHs, and stars without planets (HARPS) with ages (a) above 8 Gyr (b) between 4 and 8 Gyr and (c) below 4 Gyr, as a function of r_{birth} . *Right panel*: Relative frequency of HMPHs and ELMPHs with ages (a) above 8 Gyr (b) between 4 and 8 Gyr and (c) below 4 Gyr, as a function of r_{birth} . In (a), the last bin was excluded since it does not contain any counts for ELMPHs, HMPHs and HARPS. In (b), the first and last bins were excluded since it does not contain any counts for ELMPHs and HMPHs. In (c), the first bin was excluded since it does not contain any counts for ELMPHs and HARPS.

Chapter 5

Conclusions

In this work, the galactic birthplaces, r_{birth} , of exoplanets were inferred by considering the ages and $[\text{Fe}/\text{H}]$ of their stars. This was possible because the chemical composition of the Galaxy varies through time as a function of the galactocentric radius, meaning that each given locus of the Galaxy at any epoch has a unique chemical makeup.

For that, two samples of stars hosting planets (SWEET-Cat and CKS) and a sample of stars without any detected planets (HARPS) were taken from the spectroscopic catalogues SWEET-Cat (Santos et al. 2013), CKS (Petigura et al. 2017) and HARPS-GTO (Delgado Mena et al. 2017), respectively. The photometric data were acquired from the *Gaia* DR3 (Gaia Collaboration et al. 2022) and 2MASS (Skrutskie et al. 2006) catalogues. The astrometric data were taken from the *Gaia* DR3. From these parameters, the first step was to derive stellar luminosities. For that, the reddening caused by interstellar dust was computed with STILISM, and the bolometric corrections on magnitudes were done with YBC. In the following step, stellar ages were estimated with PARAM, an isochrone-fitting tool with Bayesian methods. Finally, the galactic birthplaces of exoplanets were inferred following the work of Minchev et al. 2018, which consisted of projecting stars back to their birth positions based on their estimated age and metallicity.

To study the formation efficiency of low- and high-mass planets, the samples of stars hosting planets were divided into two groups based on the planetary mass they host: stars hosting low-mass planets with $M_p \leq 30 M_{\oplus}$ (LMPHs) and stars hosting high-mass planets with $M_p \geq 50 M_{\oplus}$ (HMPHs). Furthermore, a similar division was also done considering the maximum planetary mass hosted, leaving a group of stars hosting exclusively low-mass planets (ELMPHs). Then the $[\text{Fe}/\text{H}]$, age, and r_{birth} distributions of these samples were studied and compared to their non-host counterparts.

Overall, the formation frequency, calculated as the relative frequency of exoplanets, appears to increase with $[\text{Fe}/\text{H}]$. For high-mass planets, this relation is steeper than for low-mass planets. This is in agreement with the giant planet-metallicity correlation found in previous studies. Since stars imprint the metallicity of the ISM at which they were born, their metallicity is proportional

to the amount of metals in their protoplanetary disc. In turn, the large amount of metals in the disc means a higher probability of forming giant planets, as predicted by core accretion models. On the other hand, there is not much evidence of a correlation between low-mass planets and stellar metallicity. Still, the results in this work show a slight dependence for low-mass planets on stellar metallicity. Additionally, the results show that the number of non-hosts decreases with metallicity, indicating that these stars preferentially form in lower metallicity environments than stars hosting planets.

Regarding stellar age, the formation efficiency of high-mass planets appears to be age-dependent, for which it increases significantly towards younger stars. This is a result of the ISM enrichment over time, causing younger stars to have higher metallicity than older ones, favouring the formation of giant planets. On the other hand, the formation efficiency of low-mass planets seems to be almost constant with time. However, younger stars are very active, making these planets very hard to detect. This can cause the observed trend to be age-independent, which might not reflect reality. The results also suggest that the formation of non-host stars decreases with time. This means that the enrichment of the ISM favours the formation of planets.

The formation efficiency of planets decreases with r_{birth} . In particular, the dependence on galactocentric radii is stronger for high-mass planets than for low-mass planets. Furthermore, stars hosting high-mass planets appear to form at smaller r_{birth} than stars hosting low-mass planets. Nevertheless, both groups of stars hosting planets form at smaller r_{birth} than their non-host counterparts. This is in agreement with the observed ISM negative metallicity gradient, at which the inner disc has higher metallicity than the outer disc, favouring the formation of, especially, high-mass planets in the inner disc. At early times, the general formation of stars with and without planets is more concentrated at small r_{birth} , but over time, it spreads out to larger r_{birth} , in accordance with the flattening of the metallicity gradient with time. In particular, the formation efficiency of high-mass planets is lower at early times and more concentrated towards small galactocentric radii. Over time, the formation efficiency of these planets increases steeply, encompassing larger galactocentric radii, contrary to non-host stars. The latter form less over time, as the ISM enriches, and forms preferentially at larger galactocentric radii, where the metallicity is sufficient to form stars without planets. Although the formation efficiency of low-mass planets does not seem to depend on time, it does appear to depend subtly on galactocentric radii. This emphasises the fact that the low detectability of these planets in younger stars might influence the results and not reflect reality.

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