The Galactic habitable zone around M and FGK stars with chemical evolution models with dust

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ABSTRACT

Context. The Galactic habitable zone is defined as the region with highly enough metallicity to form planetary systems in which Earth-like planets could be born and might be capable of sustaining life surviving to the destructive effects of nearby supernova explosion events.

Aims. Galactic chemical evolution models can be useful tools for studying the galactic habitable zones in different systems. Our aim here is to find the Galactic habitable zone using chemical evolution models for the Milky Way disc, adopting the most recent prescriptions for the evolution of dust and for the probability of finding planetary systems around M and FGK stars. Moreover, for the first time, we will express those probabilities in terms of the dust-to-gas ratio of the ISM in the solar neighborhood as computed by detailed chemical evolution models.

Methods. At a fixed Galactic time and Galactocentric distance we determine the number of M and FGK stars having Earths (but no gas giant planets) which survived supernova explosions, using the formalism of our Paper I.

Results. The probabilities of finding terrestrial planets but not gas giant planets around M stars deviate substantially from the ones around FGK stars for supersolar values of [Fe/H]. For both FGK and M stars the maximum number of stars hosting habitable planets is at 8 kpc from the Galactic Centre, if destructive effects by supernova explosions are taken into account. At the present time the total number of M stars with habitable planets are \( \lesssim 10 \) times the number of FGK stars. Moreover, we provide a sixth order polynomial fit (and a linear one but more approximated) for the relation found with chemical evolution models in the solar neighborhood between the [Fe/H] abundances and the dust-to-gas ratio.

Conclusions. The most likely Galactic zone to find terrestrial habitable planets around M and FGK stars is the annular region 2 kpc wide centred at 8 kpc from the Galactic center (the solar neighborhood). We also provide the probabilities of finding Earth-like planets as the function of the ISM dust-to-gas ratio using detailed chemical evolution models results.

Key words. Galaxy: abundances - Galaxy: evolution - planets and satellites: general - ISM: general

1. Introduction

The Galactic habitable zone (GHZ) has been defined as the region with sufficiently high abundances of heavy elements to form planetary systems in which terrestrial planets could be found and might be capable of sustaining life. Therefore, the chemical evolution of the Galaxy plays a key role to properly model the GHZ evolution in space and in time. The minimum metallicity needed for planetary formation, which would include the formation of a planet with Earth-like characteristics (firstly discussed by Gonzalez et al. 2001) has been fixed at the value of 0.1 Z⊙ by the theoretical work of Johnson & Li (2012).

In the last years several purely chemical evolution models (Lineweaver 2001, Lineweaver et al. 2004, Prantzos 2008, Carigi et al. 2013, Spitoni et al. 2014) have studied the habitable zones of our Galaxy as functions of the Galactic time and Galactocentric distances. In particular Spitoni et al. (2014, hereafter Paper I), in which radial gas flows were included, confirmed the previous results of Lineweaver at al. (2004) and found that the maximum number of stars which can host habitable terrestrial planets are in solar neighborhood, i.e. the region centered at 8 kpc, and 2 kpc wide.

Recently, the GHZ has been also studied in the cosmological context (ΛCDM) by Forgan et al. (2015), Gobat & Hong (2016), Zackrisson et al. (2016), and Vukotić et al. (2016) showing which kind of halos can give rise to galactic structures in which habitable planets could be formed.

In most of the models mentioned above (both for purely chemical evolution and cosmological models), it was considered the probability of forming planetary systems in which terrestrial planets are found without any gas giant planets or hot Jupiters, because in principle the last two planet types could destroy Earths during their evolution.

The terms giant planets, gas giants, or simply Jupiters, refer to large planets, typically >10 M⊕, that are not composed primarily of rock or other solid matter. When orbiting close to the host star they are referred to as hot Jupiters or very hot Jupiters. The “core accretion model” of giant planet formation is the most widely accepted in the literature, and the next stochastic migration due to turbulent fluctuations in the disc could destroy the terrestrial planets. Rice & Armitage (2003) showed that the formation of Jupiter can be accelerated by almost an order of magnitude
if the growing core executes a random walk with an amplitude of $\approx 0.5$ AU. Nowadays, about 3 thousands of planets have been discovered and the statistics is good enough to confirm that most of planetary systems host planets which are not present in our solar system, such as hot Jupiters or super-Earths.

In this paper we retain the assumption that gas giant planets could destroy, during their evolution, terrestrial ones (we are aware that the real effects are still uncertain). On this basis we study the GHZ using the most updated probabilities related to the formation of gas giant planets as functions of $[\text{Fe}/\text{H}]$ abundance values as well as the stellar mass for FGK and M stars. It is recent the discovery of a planetary system around the M star Trappist-1 (Gillon et al. 2016, 2017) composed by seven terrestrial planets characterized by equilibrium temperature low enough to make possible the presence of liquid water. This detection makes the habitability around M stars even more interesting.

In this paper we also compute the probabilities related to the formation of gas giant planets as functions of $[\text{Fe}/\text{H}]$ abundance values and the stellar mass for FGK and M stars with a detailed chemical evolution model for the Milky Way with dust evolution.

Even though, we know very little about the formation of planetary systems: in particular, it is not well understood the transition from a protoplanetary disc to a planetary system. In this transition, dust and gas rapidly evolve in very different ways due to many processes (Armitage 2013) such as dust growth, gas photoevaporation (Alexander et al. 2014), gas accretion onto the star (Gammie 1996). Dust plays a fundamental role in the formation of the first planetesimals, as it represents the solid compounds of the matter which can form rocky planetesimals and therefore planets.

The first fundamental step to understand and explain the origin of the observed diversity of exoplanetary systems, is to measure the stellar disc properties, especially the disc mass. Dust grains of $\mu$m are directly observed in protoplanetary discs and then, dust coagulation increase their size up to mm (Dullemond & Dominik 2005). On the other hand, observations of the gas are almost forbidden, because it is relatively cool and in molecular form.

In most cases, the mass of the gas is set starting from the one of the dust and by assuming a value for the dust-to-gas ratio. Unfortunately, this practice has several uncertainties (Williams & Best 2014). Usually, models of planetary formation use an average value of $10^{-2}$ for the initial condition of the dust-to-gas ratio in the protoplanetary disc (Bohlind et al. 1978).

Furthermore, the formation rate of gas giant planets seems to be related to the metallicity of the hosting stars (Fisher & Valenti 2005, Johnson et al. 2010, Mortier et al. 2012, Gaidos & Mann 2014). Moreover, even if Buchhave et al. (2012) showed that planets with radii smaller than 4 $R_\oplus$ do not present any metallicity correlation, the theoretical work of Johnson & Li (2012) predicted that first Earth-like planets likely formed from circumstellar discs with metallicities $Z \geq 0.1$ $Z_\odot$.

With this work, providing the time evolution of the dust, we discuss the connection between the metallicity of the ISM and the dust-to-gas ($D^2$) ratio (especially for the solar neighborhood). In this way, we can link the metallicity of stars, which is observationally related to the probability of the presence of hosted planets, with the initial dust-to-gas ratio of the protoplanetary discs (the dust-to-gas ratio of the ISM at the instant of the protoplanetary disc formation).

The paper is organized as follows: in Section 2 we present the probabilities of terrestrial planets around M and FGK stars. In Section 3 we describe the Milky Way chemical evolution model with dust and we present the main results in Section 4. Finally, our conclusions are summarized in Section 5.

### 2. The probabilities of terrestrial planets around M and FGK stars

Buchhave et al. (2012) who analyzed the mission Kepler, found that the frequencies of the planets with earth-like sizes are almost independent of the metallicity of the host star up to $[\text{Fe}/\text{H}]$ abundance values smaller than 0.5 dex.

In agreement with these observations, Prantzos (2008) fixed the probability of forming Earth-like planets ($P_{FE}$, where $FE$ stands for Forming Earths) at value of 0.4 for $[\text{Fe}/\text{H}] \gtrsim -1$ dex, otherwise $P_{FE} = 0$ for smaller values of $[\text{Fe}/\text{H}]$. This assumption was also adopted by Carigi et al. (2013) and Paper I. The value of $P_{FE} = 0.4$ was chosen to reproduce the metallicity integrated probability of Lineweaver et al. (2001).

In Paper I it was considered the case in which gaseous giant planets with same host star can destroy terrestrial planets (i.e. during their migration path). Armitage (2003) pointed out the potentially hazardous effects of the gas giant planet migration on the formation of Earth-like ones, and suggested that these planets preferentially exist in systems where massive giants did not migrate significantly. Matsumura et al. (2013) studying the orbital evolution of terrestrial planets when gas giant planets become dynamically unstable, showed that Earth-like planets far away from giants can also be removed.

On the other hand, various numerical simulations found that the formation of earths is not necessarily prevented by the gas giant planet migration, when eccentricity excitation timescales for (proto-)terrestrial planets are long compared to migration timescales of giant planets (e.g., Manell & Sigurdsson 2003; Lufkin et al. 2006; Raymond et al. 2006). The adopted probability of formation of a gaseous giant planet as the function of the iron abundance in the host star is taken by Fischer & Valenti (2005) as:

$$P_{GGP}([\text{Fe}/\text{H}]) = 0.03 \times 10^{2 \times [\text{Fe}/\text{H}]}.$$  \hspace{1cm} (1)

A possible theoretical explanation is that the high metallicity observed in some stars hosting giant planets represent the original composition that protostellar and protoplanetary molecular clouds were formed. In this scenario, the higher the metallicity of the primordial cloud, the proportion of dust to gas in the protoplanetary disc. This facilitates the condensation and accelerates the protoplanetary accretion before the disc gas is lost (Pollack et al. 1996). Giant planets are subsequently formed by runaway accretion of gas onto such rocky cores with $M \approx 10M_\oplus$, rather than by gravitational instabilities in a gaseous disk which predicts formation much less sensitive to metallicity (Boss, 2002).

The novelty of this work is to consider the following new probabilities for gas giant planets formation found by Gaidos & Mann (2014) and used by Zackrisson et al. (2016)
around FGK and M stars which are functions also of the masses of the hosting stars:

\[ P_{GGP/FGK}([\text{Fe/H}], M_\star) = 0.07 \times 10^{1.8[H/\text{Fe}]} \left( \frac{M_\star}{M_\odot} \right), \quad (2) \]

for the FGK stars, and

\[ P_{GGP/M}([\text{Fe/H}], M_\star) = 0.07 \times 10^{1.06[H/\text{Fe}]} \left( \frac{M_\star}{M_\odot} \right), \quad (3) \]

and for M stars, where \( M_\star \) is the mass of the host star in units of solar masses.

We assume that the range of masses spanned by M type stars is the following one: \( 0.08 \leq \frac{M_\star}{M_\odot} \leq 0.45 \). For the FGK the range is: \( 0.45 \leq \frac{M_\star}{M_\odot} \leq 1.40 \).

The probability of forming terrestrial planets around FGK/M stars but not gaseous giant planets is given by:

\[ P_{E/FGK,M} = P_{FE} \times (1 - P_{GGP/FGK,M}). \quad (4) \]

Here, we make the conservative assumption of Prantzos (2008) and Paper I that the \( P_{FE} \) probability is constant at the value of 0.4 for all stellar types, including M and FGK stars. On the other hand, Zackrisson et al. (2016) presented results where \( P_{FE} = 0.4 \) around FGK stars, and \( P_{FE} = 1 \) around M stars.

The possibility of finding habitable planets around M-dwarf has long been debated, due to differences between the unique stellar and planetary environments around these low-mass stars, as compared to hotter, more luminous Sun-like stars (Shields et al. 2016). The presence of multiple rocky planets (Howard et al. 2012), with roughly a third of these rocky M-dwarf planets orbiting within the habitable zone, supports the hypothesis of the presence of liquid water on their surfaces. On the other hand, flare activity, synchronous rotation, and the likelihood of photosynthesis could have a severe impact on the habitability of planets hosted by M dwarf stars (Tarter et al., 2007).

We define \( P_{GHZ}(FGK/M, R, t) \) as the fraction of all FGK/M stars having around Earths (but no gas giant planets) which survived supernova explosions as a function of the Galactic radius and time:

\[ P_{GHZ}(FGK/M, R, t) = \frac{\int_0^t SFR(R, t')P_{E/FGK,M}(R, t')P_{SN}(R, t')dt'}{\int_0^t SFR(R, t')dt'}. \quad (5) \]
This quantity must be interpreted as the relative probability to have complex life around one star at a given position, as suggested by Prantzos (2008).

In eq. (4) $SFR(R, t')$ is the star formation rate (SFR) at the time $t'$ and Galactocentric distance $R$, and $P_{SN}(R, t')$ is the probability of surviving supernova explosion.

We know that hard radiation originated by close-by SN explosions could lead to the depletion of the ozone layer in terrestrial atmosphere. At this point, the ultraviolet radiation from the host star can penetrate the atmosphere, altering and damaging the DNA and eventually causing the total sterilization of the planet (Gehrels et al. 2003).

For this quantity we refer to the “case 2” model of Paper I in which the SN destruction is effective if the SN rate at any time and at any radius was higher than twice the average SN rate in the solar neighborhood during the last 4.5 Gyr of the Milky Way life (we call it $<RNS_{SV}>$).

Therefore, we impose that if SN rate is larger than $2 \times <RNS_{SV}>$ then $P_{SN}(R, t) = 0$ else $P_{SN}(R, t) = 1$. We also show results when SN effects are not taken into account, in this case we simply impose $P_{SN}(R, t) = 1$ at any time and galactic radius. The “case 2” condition is almost the same as that used by Carigi et al. (2013) to describe their best models, motivated by the fact that life on Earth has proven to be highly resistant, and the real effects of SN explosions on life are still entirely uncertain.

For $<RNS_{SV}>$ we adopt the value of 0.01356 Gyr$^{-1}$ pc$^{-2}$ using the results of the S2IT model of Spitoni & Matteucci (2011) and Paper I.

Finally, we define the total number of stars formed at a certain time $t$ and Galactocentric distance $R$ hosting Earth-like planet with life $N_{\text{tot}}(FGK/M, R, t)$, as:

$$N_{\text{tot}}(FGK/M, R, t) = P_{GHZ} \times N_{\text{tot}},$$

where $N_{\text{tot}}(FGK/M, R, t)$ is the total number of stars created up to time $t$ at the Galactocentric distance $R$.

### 3. The Milky Way chemical evolution model with dust

To trace the chemical evolution of the Milky Way we adopt an updated version of the two-infall model of Paper I in which we consider the dust evolution using the new prescriptions of Gioannini et al. (2017).

#### 3.1. The two infall model of Paper I

The chemical evolution model of Paper I is based on the classical two-infall model of Chiappini et al. (2001). We describe here the main characteristics of the model.

We define $G_i(t) = G(t)X_i(t)$ as the fractional mass of the element $i$ at the time $t$ in the ISM, where $X_i(t)$ represents the abundance of the element $i$ in the ISM at the time $t$. The temporal evolution of $G_i(t)$ in the ISM is described by the following expression:

$$\dot{G}_i(t) = -\psi(t)X_i(t) + R_i(t) + \dot{G}_{i,\text{inf}}(t).$$

The first term in the right side of eq. (7) represents the rate at which the fraction of the element $i$ is subtracted by the ISM due to the SFR process. $R_i(t)$ is the returned mass fraction of the element $i$ injected into the ISM from stars thanks to stellar winds and SN explosions. This term takes into account nucleosynthesis prescriptions concerning stellar yields and supernova progenitor models. The third term of eq. (7) represents the rate of the infall of the element $i$. The infalling gas is not pre-enriched and has a pure primordial composition.

The two-infall approach is a sequential model in which the halo-thick disc and the thin disc form by means of two independent infall episodes of primordial gas following this infall rate law:

$$\dot{G}_{i,\text{inf}}(t) = a(r)e^{-t/\tau_H} + b(r)e^{-(t-t_{\text{max}})/\tau_D(r)},$$

where $\tau_H$ is the typical timescale for the formation of the halo and thick disc and it is fixed to the value of 0.8 Gyr, while $t_{\text{max}} = 1$ Gyr is the time for the maximum infall onto the thin disc. The coefficients $a(r)$ and $b(r)$ are obtained by imposing a fit to the observed current total surface mass density in the thin disc as a function of Galactocentric distance given by:

$$\Sigma(r) = \Sigma_0 e^{-R/RF},$$

where $\Sigma_0 = 531 M_\odot$ pc$^{-2}$ is the central total surface mass density and $R_D = 3.5$ kpc is the scale length. Moreover, the formation timescale of the thin disc $\tau_D(r)$ is assumed to be a function of the Galactocentric distance, leading to an inside-out scenario for the Galaxy disc build-up. In particular, we assume that:

$$\tau_D(r) = 1.033 R(kpc) - 1.267 \text{Gyr}.$$
The assumed IMF is the one of Scalo (1986), which is assumed constant in time and space.

The adopted law for the SFR is a Schmidt (1959) like one:

$$\Psi \propto \nu \Sigma_{\text{gas}}^k (r, t),$$

(11)

here $$\Sigma_{\text{gas}}(r, t)$$ is the surface gas density with the exponent $$k$$ equal to 1.5 (see Kennicutt 1998; and Chiappini et al. 1997). The quantity $$\nu$$ is the efficiency of the star formation process, and is constant and fixed to be equal to 1 Gyr $$^{-1}$$. The chemical abundances are normalized to the Asplund et al. (2009) solar values.

### 3.2. Evolution of dust

Our chemical evolution model also traces the dust evolution in the interstellar medium (ISM). Defining $$G_{i, \text{dust}}(t)$$, we can thus write the equation for dust evolution as follows:

$$G_{i, \text{dust}}(t) = -\psi(t)X_{i, \text{dust}}(t) + \delta_i R_i(t) + \left( \frac{G_{i, \text{dust}}(t)}{\tau_{\text{accr}}} \right) - \left( \frac{G_{i, \text{dust}}(t)}{\tau_{\text{destr}}} \right).$$

(12)

The right hand of this equation contains all the processes which govern the so called “dust cycle”: the first term represents the amount of dust removed from the ISM due to star formation, the second takes into account dust pollution by stars while the third and fourth terms represent dust accretion and destruction in the ISM, respectively. In this work, we used the same prescriptions used in Gioannini et al. (2017). Dust production are provided by taking into account condensation efficiencies $$\delta_i$$ as provided by Piovan et al. (2011).

1 The condensation efficiency ($$\delta_i$$) represents the fraction of an element $$i$$ expelled from a star which goes into the dust phase of the ISM.

The dust yields $$\delta_i R_i(t)$$ are not only metallicity dependent but also depend on the mass of the progenitor star. In this work we consider as dust producers Type II SNe ($$M_\star > 8 M_\odot$$) and low-intermediate mass stars ($$1.0 M_\odot < M_\star < 8.0 M_\odot$$). Concerning dust accretion and destruction we calculated the metallicity dependent timescales for these processes ($$\tau_{\text{accr}}$$ and $$\tau_{\text{destr}}$$) as described in Asano et al. (2013). For a more detailed explanation on dust prescriptions or dust chemical evolution model we address the reader to Gioannini et al. (2017).
4. Results

First, in this Section we present the main results of our Milky Way chemical evolution model in presence of dust. Moreover, the \( P_{E/F\text{GK},M} \) probabilities of finding Earth-like planets but not gas giant ones around FGK and M stars of Gaidos & Mann (2014) computed with detailed chemical evolution models for the Galactic disc at different Galactocentric distances are shown. We express these probabilities in terms of the dust-to-gas ratio \( (\frac{\nu}{\rho}) \) obtained by our ISM chemical evolution models. Finally, we present the maps of habitability of our Galaxy as functions of the galactic time and Galactocentric distances in terms of the total number of FGK and M stars which could host habitable Earth like planets and not gas giant planets.

4.1. The Milky Way disc in presence of dust

In Fig. 1 we show the time evolution of the star formation rate (SFR) (panel A), of \([\text{Fe/H}]\) abundances (panel B), of SN rates (panel C), and finally of the total dust (panel D) as functions of the Galactocentric distance. In panel A) we see the effect of the inside-out formation on the SFR in the thin disc phase. During the halo-thick disc phase (up to 1 Gyr since the beginning of the star formation) all the Galactocentric distances show the same star formation history (for all radii we assume the same surface gas density and same formation time-scales in the halo-thick disk phase, for details see Section 3).

In the inner regions the SFR in the thin disc phase is higher because of the larger gas density and shorter time-scales of gas accretion compared to the outer regions. Indeed, in the outer regions it is more evident the effect of the threshold in the gas density: the SFR goes to zero when the gas density is below the threshold. We notice also that the in the halo-thick disc phase we have the same SFR history at all Galactocentric distances.

In panel B) it is shown the “age-metallicity” relation in terms of \([\text{Fe/H}]\) ratio vs Galactic time. It is clear also in this case the effects of the inside-out formation: the inner regions exhibit a faster and more efficient chemical enrichment with higher values of \([\text{Fe/H}]\). Actually, at early times, in correspondence of the beginning of the second infall of gas (thin disc phase) there is a drop of the \([\text{Fe/H}]\) abundance values. This drop is more evident in the inner regions of the Galactic disc. This is due to the fact that in the inner regions the second infall of primordial gas related to the thin disc phase is more massive and on shorter time-scales, therefore the chemical abundances are more diluted at the beginning of the thin disc phase in the inner Galactic regions, compared to the external ones.

In panel C) of Fig. 1 we present the total SN rates as functions of the Galactic time and Galactocentric distances. With the red line we label the limit adopted in this paper and in Paper I to take into account the destruction effects of SN explosions on the Galactic habitable zones modeling \( (2 < R_{SN_{SV}} >) \). Above this SN rate limit we assume that there is zero probability to have life on a terrestrial planet.

Finally in panel D) of Fig. 1 we show the time evolution of the total surface mass density of dust at different Galactocentric radii. Dust production by stars is the main source of dust in the early phases of the Milky Way evolution. For this reason, in the inner regions, the dust amount is higher because of the large production by Type II SNe, during the initial burst of star formation, as visible in panel A). On the other hand, dust accretion becomes important at later epochs, and the dust mass tends to increase at all Galactocentric distances. The observed oscillation of the model occurs when the rates of dust accretion and dust destruction are comparable. In fact, in this case there is a gain of the total mass surface density of dust provoked by the dust growth, rapidly followed by a decreasing due to the dust destruction rate, which exceeds dust accretion. This turnover between those processes occurs especially in the quiescent phases of the Galactic evolution.

4.2. The computed probabilities \( P_{GGP/F\text{GK},M} \) with the two infall chemical evolution model

To compute the probabilities \( P_{GGP/F\text{GK},M} \) presented in eqs. (2) and (3) with our chemical evolution model we consider the weighted values on the IMF using the following expressions:

\[
< P_{GGP/F\text{GK}}(R, t) >_{IMF} = 0.07 \times 10^{1.8}[\text{Fe/H}](R, t)_{model} \left( \frac{M_{\star, F\text{GK}}}{M_{\odot}} >_{IMF} \right), \tag{13}
\]

for the FGK stars, and

\[
< P_{GGP/M}(R, t) >_{IMF} = 0.07 \times 10^{1.06}[\text{Fe/H}](R, t)_{model} \left( \frac{M_{\star, M}}{M_{\odot}} >_{IMF} \right), \tag{14}
\]

for M stars.

The \([\text{Fe/H}](R, t)_{model}\) quantity is the computed iron abundance with our chemical evolution model adopting the Scalo (1986) IMF at the Galactic time \( t \) and Galactocentric distance \( R \).

Therefore, to compute \( < P_{GGP/M} >_{IMF} \) and \( < P_{GGP/F\text{GK}} >_{IMF} \) quantities we have only to know the weighted stellar mass on the IMF in the mass range of M stars and FGK stars, respectively. The weighted stellar masses on the Scalo (1986) IMF are:

\[
< \frac{M_{\star, F\text{GK}}}{M_{\odot}} >_{IMF} = \frac{\int_{0.45}^{1.4} M_{\odot} m^{-1.35} dm}{\int_{0.45}^{1.4} M_{\odot} m^{-2.35} dm} = 0.72584 \tag{15}
\]

and

\[
< \frac{M_{\star, M}}{M_{\odot}} >_{IMF} = \frac{\int_{0.08}^{0.45} M_{\odot} m^{-1.35} dm}{\int_{0.08}^{0.45} M_{\odot} m^{-2.35} dm} = 0.15504. \tag{16}
\]

In Fig. 2 we show the evolution of \( < P_{GGP/F\text{GK}} >_{IMF} \) and \( < P_{GGP/M} >_{IMF} \) probabilities as the function of the \([\text{Fe/H}]\) abundance ratio computed at different Galactocentric distances using our chemical evolution models. Because of the inside-out formation, the inner regions exhibit a faster and more efficient chemical enrichment. In fact, the model computed at 4 kpc reaches, at the present time, \([\text{Fe/H}]\) value of 0.55 dex, instead of at 20 kpc the maximum \([\text{Fe/H}]\) is
Fig. 5. Upper panels: The probability $<P_{\text{GHZ} > 	ext{IMF}}$ to find terrestrial habitable planets but not gas giant around FGK stars (Panel A) and M stars (Panel B) as a function of the Galactocentric radius. In this case we do not consider the destructive effects from nearby SN explosions. The color code indicates different Galactic times. Lower panels: The probability $P_{\text{GHZ}}$ to find terrestrial habitable planets but not gas giant around FGK stars (Panel C) and M stars (Panel D) as the function of the Galactocentric radius taking into account the destructive effects from nearby SN explosions. The color code indicates different Galactic times.

equal to -0.1 dex. We see that the two probabilities become to be substantially different for over-solar values in the inner regions. For instance, at the present time, i.e. at the maximum values of the [Fe/H] abundance in Panel C of Fig. 1 at 4 kpc the probabilities $<P_{\text{GGP/FGK} > 	ext{IMF}}$ and $<P_{\text{GGP/M} > 	ext{IMF}}$ show the values of 0.43 and 0.04, respectively.

4.3. The dust-to-gas ratio ($D/G$)

In this Subsection we provide a useful theoretical tool to set the proper initial conditions for the formation of protoplanetary discs. As underlined in Section 1, while dust grains of $\mu$m are directly observed in protoplanetary discs, on the other hand, the amount of gas mass is set starting from the one of the dust and by assuming a value for the dust-to-gas ratio. Unfortunately, this practice has several uncertainties (Williams & Best 2014). In this subsection, we connect the evolution of the dust to gas ratios at different Galactocentric distances with the chemical enrichment expressed in terms of [Fe/H]. Because of the well known “age-metallicity” relation reported in the Panel C) of Fig. 1, the dust-to-gas ratio ($D/G$)(t) as a function of [Fe/H] at different Galactocentric distances. As expected, higher metallicities are reached in the inner radii, where the star formation is higher. The dust-to-gas ratio ($D/G$) increases in time for two reasons: the first is that dust production in star forming regions is high, especially from Type II SNe, while the second is related to dust accretion. Dust accretion is a very important process occurring in the ISM and it becomes the most important one as the critical metallicity is reached.

As dust grains are formed by metals, dust accretion becomes more efficient as the metallicity in the ISM increases. For this reason at high values of [Fe/H], we found higher values of dust-to-gas ratio. The relation between the [Fe/H] and the dust-to-gas ratio is important because it can provide the probability of planet formation depending on the amount of dust in the ISM and, on the other hand, provides an estimate of the dust-to-gas ratio in the ISM during the formation of a protoplanetary disc.

\footnote{The critical metallicity is the metallicity at which the contribution of dust accretion overtakes the dust production from stars (Asano et al. 2013).}
The solar dust-to-gas ratio \(\left(\frac{D}{G}\right)_\odot\) value predicted by our model (model value computed in the solar neighborhood at 9.5 Gyr) is 0.01066.

In the lower panel of Fig. 4 we show the \(\frac{D}{G}\) as a function of the [Fe/H] values only for the shell centered at 8 kpc and 2 kpc wide (the solar neighborhood). In the same plot the sixth degree polynomial fit which follows exactly the [Fe/H] vs \(\frac{D}{G}\) in the range of [Fe/H] between -1 dex and 0.5 dex is presented. The expression of this fit is the following one:

\[
[\text{Fe/H}] = \sum_{n=0}^{6} \alpha_n \left(\frac{D}{G}\right)^n
\]

(17)

All the coefficients \(\alpha_n\) and \(n\) are reported in the footnote:\footnote{[Fe/H]=-1.48 + 1.05 \times 10^4 \left(\frac{D}{G}\right) - 4.91 \times 10^5 \left(\frac{D}{G}\right)^2 + 1.141 \times 10^6 \left(\frac{D}{G}\right)^3 - 1.32 \times 10^{10} \left(\frac{D}{G}\right)^4 + 7.57 \times 10^{11} \left(\frac{D}{G}\right)^5 - 1.69 \times 10^{13} \left(\frac{D}{G}\right)^6}

We found that for [Fe/H] values higher than -0.6 dex a linear fit is able to reproduce pretty well the computed [Fe/H] vs \(\left(\frac{D}{G}\right)\) relation in the solar vicinity.

The equation of the linear fit reported in the lower panel of Fig. 4 is:

\[
[\text{Fe/H}] = 96.49 \left(\frac{D}{G}\right) - 0.92.
\]

(18)

This relation is important to connect the dust-to-gas ratio with the [Fe/H] abundance. If we combine it with eq. 4 we obtain the probability of having terrestrial planets but not gas giant ones depending on the amount of dust in the ISM.

4.4. The \(P_{GHZ}\) values around FGK and M stars

In the upper panels of Fig. 5 (A and B) we show the evolution in time of the \(P_{GHZ}\) values for FGK and M stars as functions of the Galactic center distances in the case when SN destruction effects are not taken into account.

We notice that the \(< P_{GHZ,FGK} >_{1MF}\) and \(< P_{GHZ,M} >_{1MF}\) probabilities are identical at large Galactic center distances. This is due to the fact that, as shown in Fig. 3 the \(< P_{E,FGK} >_{1MF}\) and \(< P_{E,M} >_{1MF}\) probabilities are similar for sub-solar values of [Fe/H]. The chemical evolution in the outer parts of the Galaxy, because of the inside-out formation, is slow and with longer time scales. The maximum values of [Fe/H] are smaller than in the inner region and sub-solar (see the “age-metallicity” relation reported in panel B of Fig. 1).

Moreover, in the inner regions \(< P_{GHZ,M} >_{1MF}\) and \(< P_{GHZ,FGK} >_{1MF}\) probabilities become to be different only for Galactic times larger than 8 Gyr. As expected the higher probabilities are related to the M stars. Even if the \(< P_{E,FGK} >_{1MF}\) and \(< P_{E,M} >_{1MF}\) probabilities are substantially different for [Fe/H] > 0.2 (see Fig. 3), the two associated \(P_{GHZ}\) probabilities are similar.

This is due to the definition of \(P_{GHZ}(t)\): at each Galactic time the SFR \(\times P_{E}\) quantity is integrated from 0 to \(t\). In other words, we are weighting the \(P_E\) quantity on the SFR. From panel C) of Fig. 4 it is clear that the peak of the SFR in the inner regions (annular region between 3 and 7 kpc) is around 3 Gyr. From the “age-metallicity” relation reported in panel B) of Fig. 4, we derive that at this age the mean Galactic [Fe/H] is -0.5 dex. At this metallicity, as stated above, the \(P_{E,FGK}\) and \(P_{E,M}\) values are almost the same. This is the reason why the two \(P_{GHZ}\) probabilities are similar even at late time in the inner regions.

In the lower panels of Fig. 5 (C and D) we show that, the \(P_{GHZ}\) probabilities for FGK and M stars as functions of the Galactic center distances and time, when the SN destruction effects have been taken into account, are almost identical. As found in Paper I the Galactic center distance with the highest probability that a star (FGK or M type) hosts a terrestrial planet but not gas giant ones is 10 kpc.

4.5. THE GHZ maps for FGK and M stars

In order to recover the total number of stars at the Galactic time \(t\) and Galactocentric distance \(R\) hosting habitable planets, it is required the total number of stars created up to time \(t\) at the Galactocentric distance \(R\) (the \(N_{\star,tot}\) quantity in eq. 9).
Our chemical evolution model very well reproduces the observed total local stellar surface mass density of $35 \pm 5$ $M_\odot$ pc$^{-2}$ (Gilmore et al. 1989, Spitoni et al. 2015). In fact, our predicted value for the total surface mass density of stars is $35.039$ $M_\odot$ pc$^{-2}$. Moreover, we find that this value concerning only to M stars is $24.923$ $M_\odot$ pc$^{-2}$ and the one for FGK stars is $9.579$ $M_\odot$ pc$^{-2}$.

In Fig. 6 we show the number of FGK stars (upper panel) and M stars (lower panel) hosting habitable terrestrial planets but not gas giant planets as functions of the Galactic time and Galactocentric radius (the quantity $N_{*,life}$ of eq. 4).

We notice that for both FGK and M stars, the GHZ maps, in terms of the total number of stars hosting planets with life, peaks at 8 kpc. On the other hand, as we have seen above the maximum fraction of stars which can host habitable terrestrial planets peaks at 10 kpc (see panels C and D of Fig. 5).

The reason why the GHZ peaks at galactocentric distances smaller than in the case when it is expressed in terms of fraction of stars is the following one: in the external regions the number of stars formed at any time is smaller than in the inner regions because of the the smaller SFR. This is in agreement with the results of Prantzos (2008) and Paper I.

We see that, at the present time, in the solar neighborhood the number $N_{*,M,life}/N_{*,FGK,life}$=10.60. This ratio is consistent with the IMF we adopt in our model. In fact, the ratio between the fraction of M stars over FGK stars (by number) in a newborn population adopting a Scalo IMF is:

$$\left( \frac{M_{\text{number}}}{FGK_{\text{number}}} \right) = \frac{0.45}{0.08} \frac{M_\odot}{m} \left( \frac{m}{M_\odot} \right)^{-2.35} \left( \frac{m}{M_\odot} \right)^{-2.35} = 11.85.$$

Finally, the predicted local surface mass density of M stars hosting habitable planets predicted by our model is $5.446$ $M_\odot$ pc$^{-2}$, and the value for FGK stars is $2.40$ $M_\odot$ pc$^{-2}$.

5. Conclusions

In this work we investigated the Galactic habitable zone of the Milky Way adopting the most updated prescriptions for the probabilities of finding terrestrial planets and gas giant planets around FGK and M stars. To do that we adopted a chemical evolution model for the Milky Way which follows the evolution of the chemical abundances both in the gas and dust.

The main results can be summarized as follow:

- Adopting the Scalo (1986) IMF the probabilities of finding gas giant planets around FGK and M stars computed with the two-infall chemical evolution model of Paper I begin to be different for supersolar values of [Fe/H]. In particular, substantial differences are present in the annular region centred at 4 kpc from the Galactic centre.
- We provide for the first time a sixth order polynomial fit (and a linear one but more approximated) for the relation found in the chemical evolution model in the solar neighborhood between the [Fe/H] abundances and the dust-to-gas ratio ($\mathcal{D}/\mathcal{G}$). With this relation it is possible to express the Gaidos & Mann (2014) probabilities of finding gaseous giant planets around FGK or M stars in terms of the gas to dust ratio $\mathcal{D}/\mathcal{G}$.
- We provide a useful theoretical tool to set the proper initial condition for the formation of protoplanetary disc connecting the evolution of the dust-to-gas ratios at different Galactocentric distances with the chemical enrichment expressed in terms of [Fe/H].
- The probabilities that a FGK or M star could host habitable planets are roughly identical. Slightly differences arise only at Galactic times larger than 9 Gyr where the probability of finding gas giant planets around FGK becomes substantially different from the one associated to M stars.
- As found by Paper I, adopting the same prescriptions for the destructive effect from close-by SN explosions, the larger number of FGK and M stars with habitable planets are in the solar neighborhood.
- At the present time the total number of M stars with habitable terrestrial planets without gas giant ones are $\approx 10$ times the number of FGK stars. This result is consistent with the Scalo (1986) IMF adopted here.

The Gaia mission with its global astrometry, will be crucial for the study of exoplanets. We recall the relation used in this work between the frequency of gas giant planets and the metallicity of the host star was obtained by means of the Doppler effect with the method of radial velocity, and it will be possible with Gaia to test whether this result is an observational bias or is related to real physical processes. It is estimated that Gaia will be able to find out up to $10^4$ giant planets in the solar vicinity with its global astrometry with distances spanning the range between 0.5 and 4.5 AU from the host star.

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