

New numerical determination of habitability in the Galaxy: the SETI connection

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Abstract: In this paper, we determine the habitability of Sun-like stars in the Galaxy using Monte Carlo simulations, which are guided by the factors of the Drake Equation for the considerations on the astrophysical and biological parameters needed to generate and maintain life on a planet's surface. We used a simple star distribution, initial mass function and star formation history to reproduce the properties and distribution of stars within the Galaxy. Using updated exoplanet data from the Kepler mission, we assign planets to some of the stars, and then follow the evolution of life on the planets that met the habitability criteria using two different civilization hypotheses. We predict that around 51% of Earth-like planets in the habitable zone (HZ) are inhabited by primitive life and 4% by technological life. We apply the results to the Kepler field of view, and predicted that there should be at least six Earth-like planets in the HZ, three of them inhabited by primitive life. According to our model, non-technological life is very common if there are the right conditions, but communicative civilizations are less likely to exist and detect. Nonetheless, we predict a considerable number of detectable civilizations within our Galaxy, making it worthwhile to keep searching.

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Introduction

In 1961, Frank Drake (Drake & Sobel 1994) introduced his now famous equation, an algebraic expression that gives the total number of extraterrestrial civilizations capable of communicating with Earth's inhabitants as:

$$N = R_* f_g f_p n_c f_i f_c L, \quad (1)$$

where N is the number of Galactic civilizations who can communicate with the Earth. R_* is the mean star formation rate of the Milky Way. f_g is the fraction of stars that could support habitable planets. f_p is the fraction of stars that host planetary systems. n_c are the number of planets in each system that are potentially habitable. f_i is the fraction of habitable planets where life originates and becomes complex. f_c is the fraction of life-bearing planets that develop intelligence. L is the mean lifetime of a technological civilization within the detection window.

In recent years, the astronomical parameters of Drake equation have been better constrained due to the observational advances, mainly in the discovery of a great number of exoplanets that can be used to build new and more accurate observational distribution functions. We now know of the existence of exoplanets orbiting Sun-like stars within our Galaxy (Borucki *et al.* 2012; Torres *et al.* 2015), Earth-like planets orbiting

low-mass stars within their habitable zone (HZ) (Borucki *et al.* 2013; Quintana *et al.* 2014), and more than 2000 confirmed exoplanets (exoplanets.eu).

The search for extraterrestrial intelligence (SETI) has been very controversial and all attempts to find an intelligent civilization outside our planet have been unsuccessful. This motivates theoretical studies in order to assess the feasibility of finding extraterrestrial intelligence and whether it is worthwhile investing in such searches. Past studies have used numerical methods as testbeds of hypotheses of extraterrestrial life and intelligence, using Monte Carlo realizations to study some of the factors of the Drake Equation (Forgan 2009; Forgan & Rice 2010).

With the new discoveries and the improvement of past models, we give an estimation of the number of potentially habitable planets, the probability of the existence of extraterrestrial life, from simple life to more complex intelligent life, and discuss the implications of these new results for the Kepler field of view (FOV), which is completely within the Solar neighbourhood.

We will refer as simple or primitive life to any type of life that is incapable of developing communicative technology, while an intelligent civilization is capable of communicating beyond their planet. Intelligent civilizations go through a phase of vulnerability towards events of destruction, which we will call 'vulnerable' civilizations, to finally become an 'advanced'

civilization if survived those events. We assume that these civilizations will last forever. Those definitions place humans as a ‘vulnerable’ civilization.

In this work, we propose to extend the use of the Monte Carlo Method to study the Drake equation in the light of new exoplanets discoveries. The aim of this study is to have as few free parameters as possible to obtain more accurate results. In Section 2, the stellar distributions and properties, the way the stars are generated, the planetary input data and the HZ are described. The parameters for life to evolve are discussed in Section 3, whereas in Section 4 the life algorithm is described. In Section 5, the two civilizations models are discussed; in Section 6 the results for the models and several cases are shown, and finally, the conclusions are shown in Section 7.

The galactic model

The Solar neighbourhood (SN) is the space associated with a cylinder centred at the Sun and perpendicular to the Milky Way disc. This Solar Cylinder is located at ~ 8 kpc from the Galactic centre, with a radius of 1 kpc (Carigi 2015). Working within the SN is appropriate because the observational data used in this work has been collected from areas inside the SN [e.g., Kepler field and initial mass function (IMF)]. This region can be extended to cover an annular region around the Galaxy as the galactic properties only depend radially from the centre of the galactic disc and above/below the midplane of the Galaxy. Therefore we defined the Solar Galactocentric Region (SGR) as an annular region between 7 and 9 kpc from the Galactic centre. This work will only consider the stars within this region.

We only consider planets around Sun-like stars (F, G and K), because most of the confirmed Kepler exoplanets orbit those stars (exoplanets.eu, September 2016). To reproduce the mass distribution of the stars in the SGR, we used the IMF from Miller & Scalo (1979) in its Gaussian form (see Fig. 1), as follows:

$$\xi(M) = C_0 e^{-1.09(\log M + 1.02)^2}, \quad (2)$$

where M is the mass of the star expressed in Solar masses, the quantity $C_0 = 10^{10}$ is a normalization constant which is obtained by considering the total disc mass of $4.2 \times 10^{10} M_\odot$ estimated by Binney & Tremaine (2008). Then, the total number of stars in the disc was calculated using the equation above, yielding to a total of 1.2×10^{10} stars. The spatial distribution of stars is not uniform; therefore, it is necessary to calculate the number of stars within the SGR using a stellar number density distribution. We used the Carroll & Ostlie (2006) distribution, which gives the distribution of stars above the midplane and radially from the centre of the Galaxy, calculated using:

$$n(z, R) = n_0(e^{-z/z_{\text{thin}}} + 0.085e^{-z/z_{\text{thick}}})e^{-R/h_R}, \quad (3)$$

where z is the height above the midplane and R is the radial distance from the centre of the Galaxy, the constant $h_R = 2.25$ kpc is the radial disc scale length, $z_{\text{thin}} = 350$ pc is the thin disc scale height, $z_{\text{thick}} = 1000$ pc is the thick disc scale height. The

quantity n_0 is the normalization constant that is obtained integrating equation (3) over the complete volume of the galactic disc for $2.5 \text{ kpc} \leq R \leq 15 \text{ kpc}$, and $0 \leq z \leq 1000 \text{ pc}$. Then, we integrated over the whole SGR volume with a radius between 7 and 9 kpc, which yielded to 1.5 billion stars in the SGR. Finally, we calculated how many of those stars were F, G or K ($0.5 - 1.3 M_\odot$) using the IMF [equation (2)], which yielded approximately 400 million of stars with a total mass of $3.8 \times 10^8 M_\odot$.

Generating stars

An important aspect of this project is to determine the mass of the stars by means of Monte Carlo realizations. The 400 million stars are individually generated one by one, so a random function that reproduces the IMF in the range of $0.5 - 1.3 M_\odot$ is necessary. To accomplish it, we make single stars using a generating function extracted from equation (2) as follows:

$$M(X) = 1.087 \exp\left[\frac{\text{erf}^{-1}(0.88 - (X/0.63))}{0.45}\right], \quad (4)$$

where X is a random number between 0.314 and 0.612 to cover the range of masses between 0.5 and $1.3 M_\odot$. Once we determine the mass, we calculate the stellar properties using the homology relations. The stellar radius can be calculated using (Hansen *et al.* 2004):

$$R_\star = R_\odot \left[\frac{M_\star}{M_\odot}\right]^{(n-1)/(n+3)}, \quad (5)$$

where n depends on the mass of the star. For low mass stars ($M \leq 1.1 M_\odot$) the energy is generated primarily by the $p-p$ chain and $n = 4$. For hotter stars ($M > 1.1 M_\odot$) the energy is generated primarily by the CNO cycle and $n = 16$. The luminosity is calculated using the mass-luminosity relation:

$$L_\star = L_\odot \left[\frac{M_\star}{M_\odot}\right]^3. \quad (6)$$

The main sequence lifetime is:

$$t_{\text{MS}} = t_{\text{MS},\odot} \left[\frac{M_\star}{M_\odot}\right]^{-2.5}. \quad (7)$$

The stellar effective temperature is calculated as:

$$T_\star = \left[\frac{L_\star}{4\pi R_\star^2 \sigma_{\text{SB}}}\right]^{1/4}. \quad (8)$$

The main properties of interest are the effective temperature and the main sequence lifetime as they will give us information about the stellar HZ and the time that potential habitable planets have to develop life (see Fig. 2), respectively.

The stars were generated chronologically in bins of 0.4 billion years to reconstruct the star formation history of the Milky Way (Rocha-Pinto *et al.* 2000) (see Fig. 3), and located randomly in the SGR.

Planetary systems

In February 2014, NASA’s Kepler mission announced the discovery of around 700 exoplanets and this number has increased

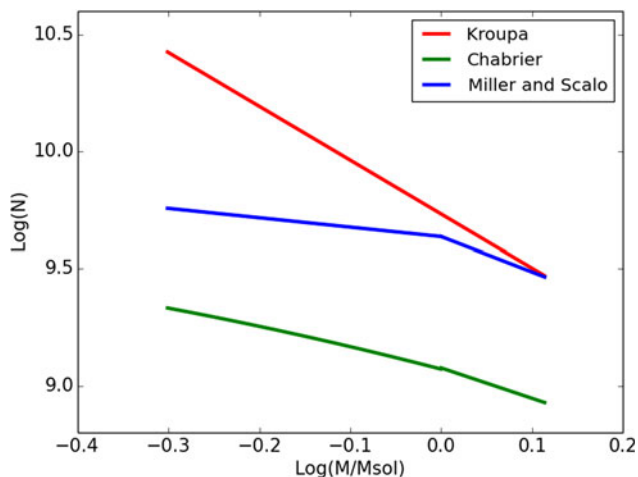


Fig. 1. Comparison of different initial mass functions: Miller & Scalo (1979, blue line), Kroupa (2001, red line) and Chabrier (2003, green line).

ever since. Whereas the last study similar to ours, Forgan (2009), had information concerning only 300 exoplanets. At the time of writing this study, ~ 2000 exoplanets have been confirmed (exoplanets.eu, September 2016). Although cannot completely eliminate observational biases, the use of observational distributions in this study fits well with our conservative model, as it can give a lower limit to the number of inhabited planets. The proportion of Earth-like planets to more massive planets may really be much higher, since it is easier to detect massive planets. For this work, we selected exoplanets with radii between 1 and $16R_{\oplus}$ and whose host star had a mass of $0.5\text{--}1.3M_{\odot}$, which yielded the 1726 exoplanets used in this work. The probability of a star to host a planet was obtained from the Kepler Mission FOV. There are about 136 000 main sequence stars in the FOV (Monet 1996) and using the IMF, around 34 595 should be F,G or K stars. According to the present information about exoplanets (exoplanets.eu, September 2016), there are 1636 different Sun-like stars hosting an exoplanet. So, we divided the number of Sun-like stars hosting planets in the FOV between the total number of Sun-like stars in the FOV and that yielded to a 4.73% chance for a star to host a planet. The radius and orbital period of each planet was randomly sampled from the distributions shown in Figs. 4 and 5, constructed from the exoplanets catalogue.

Habitable zone

The HZ is defined as the region where a rocky planet can maintain liquid water on its surface (Kasting *et al.* 1993). The HZ has two boundaries, the inner and the outer edge. The inner edge is known as the water-loss limit or runaway greenhouse, where the temperature exceeds the critical temperature for water and the entire ocean evaporates. The outer edge is called the maximum greenhouse limit, where gaseous CO_2 produces its maximum greenhouse effect.

The estimation of the HZ boundaries is based on a one-dimensional (1D) radiative-convective, cloud-free climate model done by Kopparapu *et al.* (2013). They presented a

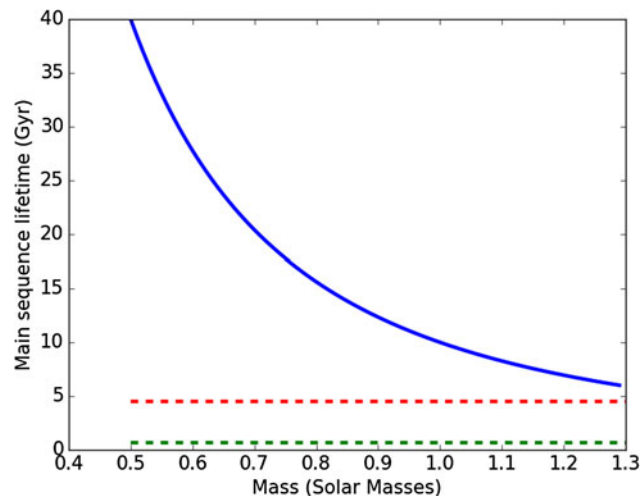


Fig. 2. The main sequence lifetime of the stars in the model, the earliest potential chemofossils dated on the Earth, 3.8 billion years ago (Mojzsis *et al.* 1996, green dotted line) and the rise of technological civilization on the Earth (red dotted line).

parametric equation to calculate the relation between HZ stellar fluxes (S_{eff}) reaching the top of the atmosphere of Earth-like planets, as follows:

$$S_{\text{eff}} = S_{\text{eff}\odot} + aT_{\star} + bT_{\star}^2 + cT_{\star}^3 + dT_{\star}^4, \quad (9)$$

where $T_{\star} = T_{\text{eff}} - 5780\text{ K}$ and the coefficients are listed in Table 3 of Kopparapu *et al.* (2013) for different habitability limits. For the purposes of this study, we used the conservative limit of the HZ. The corresponding HZ distances were calculated using the relation:

$$d = \left(\frac{L/L_{\odot}}{S_{\text{eff}}} \right)^{0.5} \text{ AU}. \quad (10)$$

Planet size

For a planet, an important factor to retain liquid water is its size. If the planet is too small, then it would not be able to retain a thick atmosphere nor liquid water on its surface. On the other hand, if the planet is too big, it can now retain H and He in its atmosphere, and so can build a very heavy atmosphere (i.e. gaseous planet), warming the surface too much and attaining a pressure too high for liquid water (Mackwell *et al.* 2013). Rogers (2015) showed that the majority of $1.6R_{\oplus}$ planets have densities that are too low to be composed of Fe and silicates alone, so we will assume that planets having a radius $R_p \leq 1.6R_{\oplus}$ are rocky and can sustain an atmosphere and liquid water on their surfaces.

The Habitable Exoplanets Catalog (phl.upr.edu) defines an Earth-like planet as one with a radius between 0.8 and $1.5R_{\oplus}$ (0.5 and $5M_{\oplus}$).

Weak assumptions

The following parameters do not have well-defined values and unfortunately observational data are limited to the Earth's

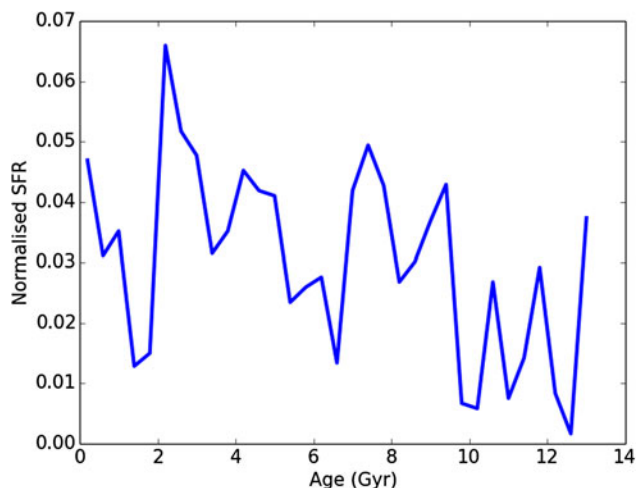


Fig. 3. The star formation history from Rocha-Pinto *et al.* (2000) produced by a single Monte Carlo simulation.

biosphere. In spite of this, the last two probabilistic parameters used in this model affect the final result significantly, so the study of what happens when used different values is easy, as it will be explained later.

Emergence and evolution of life and intelligence

A wide variety of organic molecules, from amino acids and other organic compounds extracted from meteoritic material (e.g. Pizzarello 2007) to prebiotic molecules in the interstellar medium have been discovered that are important building blocks of DNA (Zaleski *et al.* 2013).

Some studies suggest that having the right conditions and ingredients, molecules as the RNA can be formed purely as a chemical reaction path (Patel *et al.* 2015). Hence, we assume that if the habitability criteria are met the probability of the planet to harbour life, P_{life} , is 1. For other choices of P_{life} , the probability of the arise of life would be proportionally reduced, i.e., if $P_{\text{life}} = 0.5$ the planets harbouring any type of life would be halved.

Intelligence and convergent evolution

There are many studies about the evolution of intelligence focusing on monkeys and apes (e.g., Tomasello & Call 1997), since they have a very close evolutionary relationship with the humans. Because of that, the primates are not a good justification that intelligence is something that will always appear when life emerges on a planet. However, complex cognition does not only occur in primates.

Convergent evolution is the emergence of structures or similar characteristics in organisms that do not share a common ancestor with such characteristics, i.e., they emerged independently in different organisms (Reece *et al.* 2011). An important example of this phenomenon is observed with corvids and primates. Corvids, like primates, use the same cognitive tools such as: casual reasoning, flexibility, imagination and prospecting. Both families developed these qualities independently. Even more surprising is that the structure of the brains of

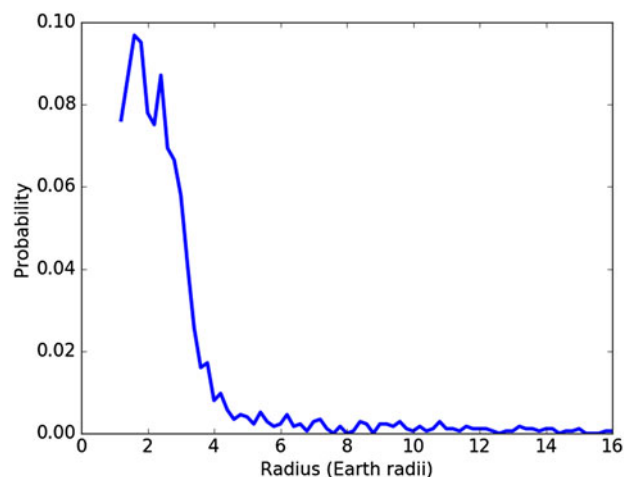


Fig. 4. Planetary mass function constructed from Kepler's confirmed exoplanets (exoplanets.eu, September 2016).

corvids and primates is very different, which has major implications because, although having a very different brain structure for humans, complex cognitive skills can be developed (Emery & Clayton 2004).

In the scope of the search for intelligent life, this supports the feasibility of the existence of another intelligent civilization, as it is observed that the emergence of intelligence is common in the evolution of life. It should be noted, that despite this, the intelligence in humans, is much more complex than that mentioned above, which, along with our morphological evolution, allows us to be the only living beings on Earth with the ability to build technology and communicate with the cosmos.

This is a very delicate assumption. If we do not consider that the rise of intelligence is only matter of time in the evolution of life, then there is no parameter to estimate an uncertainty for it. Any factor that could reduce the probability of the emergence of intelligence will proportionally reduce the number of intelligent civilizations that we could obtain with our model.

Life algorithm

The only place in the Universe where we know of the existence of life is Earth. Therefore, it is clever to apply the Copernican principle to life, and assume that life on Earth could be replicated elsewhere in the Galaxy, if the conditions are similar to those on the Earth (Clark 2000). Having said that, we take the timescales of the emergence of life on Earth and evolutionary history for modelling how life can emerge on other planets. Life has an evolutionary tendency to become more complex (e.g., Bogonovich 2011; Rospar 2013), so we assume that, allowing a sufficient amount of time, life could evolve to become an intelligent civilization if it overcomes a series of 'resets' or extinction events. This is called the 'hard step' scenario of evolution (Carter 2008). The algorithm we adopt was developed by Forgan (2009) and considers some key biological parameters that dictate the evolution of life on a planet.

If a planet is within the habitable zone and its radius is $R_p \leq 1.5 R_{\oplus}$, then it will enter the life algorithm. First, N_{stages}

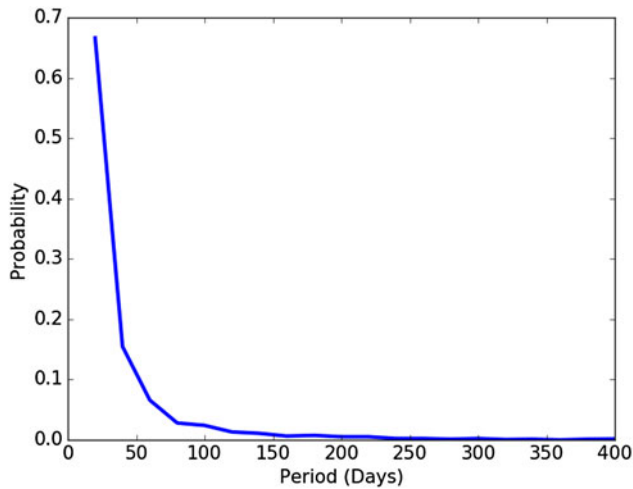


Fig. 5. Exoplanet’s orbital period distribution used in this study constructed from Kepler’s confirmed exoplanets (exoplanets.eu, September 2016).

is randomly sampled from a Gaussian distribution with the mean to be 6, and standard deviation of 1, taken from the major stages life went through on the Earth (Carter 2008). Then, the number of resets are calculated as a function of the galactocentric radius as:

$$N_{\text{resets}} = \mu_{\text{resets},0} \left(\frac{r_{\text{gal}}}{r_{\text{gal},\odot}} \right), \quad (11)$$

where $\mu_{\text{resets},0}$ is 5, reflecting the ‘Big Five’ mass extinction events in Earth’s fossil records (Raup & Sepkoski 1982). Then the time needed to complete each stage, t_i , is sampled from a Gaussian distribution with mean 0.8 Gyr, and standard deviation of 0.25 Gyr. Increasing N_{stages} or/and t_i will increase the number of planets with primitive life, as the time needed to reach intelligence would be longer. Increasing N_{resets} would lead to a higher number of planets where the biosphere is annihilated. However, to avoid the arbitrary choice of these parameters, we stick to the values used by Forgan (2009) and some modification will be done to the parameters to study their influence on the model.

In each stage, if there is a reset event, life has a chance of being annihilated. This fraction is sampled from a Gaussian distribution with a mean of 0.5 and a standard deviation of 0.25. If it is >1 , the planet’s life is completely destroyed. On the other hand, if it is <1 , the stage decreases by 1 and the intelligence timescale (time needed by life to complete all stages), t_{int} , increases a fraction of time between 0 and t_i . If there are no reset events, then t_{int} increases by t_i .

The algorithm will continue while all of the following statements are met:

1. The current stage $< N_{\text{stages}}$;
2. t_{int} is less than the main sequence lifetime of the host star;
3. annihilation has not occurred;
4. t_{int} plus the age of the host star is not greater than the present time.

Table 1. *Evolutionary intelligence index*

I_{inhabit}	Definition
−1	Biosphere which has been annihilated
0	Planet is lifeless
1	Planet has primitive life
2	Planet has vulnerable intelligent life
3	Planet had intelligent life, but it destroyed itself
4	Planet has an advanced civilization

After the algorithm ends, if all stages were completed, ‘vulnerable’ intelligent life has been reached, and it has a certain chance of surviving. If it survives, then it becomes advanced on a timescale t_{adv} . If all the stages were not completed because point 4 (from the list above) was not met, then the planet is defined to have primitive life.

Then each planet is classified with an Evolutionary Intelligence Index (Table 1), introduced by Forgan (2009), depending upon its biological history.

Signal detectability

To detect a signal from an extraterrestrial civilization we need to consider two aspects: when did the civilization arise, and how far it is from us.

Thus, to detect a live intelligent civilization signal, the next condition must be satisfied:

$$13.2 - (t_0 + t_{\text{int}}) \geq t_{\text{lt}}, \quad (12)$$

where 13.2 Gyr is the age of the Galaxy, t_0 is the age of the star and t_{lt} is the light travel time between such civilization and us. On the other hand, to detect a self-destructed civilization, this other condition must be satisfied:

$$13.2 - (t_0 + t_{\text{int}} - t_l) \geq t_{\text{lt}}, \quad (13)$$

where t_l is the lifetime of the civilization.

These conditions would give us the total number of signals that could reach the Earth only considering the time and distance as parameters. Being more realistic, not every signal would be detectable by our instruments. Loeb & Zaldarriaga (2007) calculated the maximum distance to which we could detect an intelligent civilization that produces radio broadcasts similar to ones produced by the military radars on the Earth, using some of the radio telescopes that could perform SETI studies.

These authors show that, for a given distance to the source d , the minimum power required by the transmitter to be detected on the Earth is:

$$P_{\text{min}} = C \times 3.5 \times 10^{12} \text{W} \times \left(\frac{d}{100 \text{ pc}} \right)^2 \times \left(\frac{\Delta\nu}{8 \text{ kHz}} \right)^{1/2} \times \left(\frac{t_o}{\text{month}} \right)^{-1/2}, \quad (14)$$

where C is a constant that depends on the collecting area of the telescope, $\Delta\nu$ is the bandwidth and t_o is the observation time. For the Murchinson Widefield Array (MWA) $C = 1$.

Figure 6 shows the minimum detectable radio power P_{min} , for the MWA, calculated by Loeb & Zaldarriaga (2007), for the Green Bank Telescope (GBT), a 100 m diameter

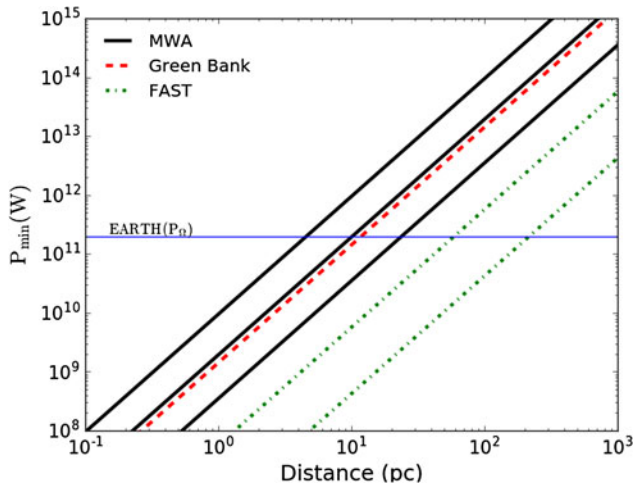


Fig. 6. Minimum detectable radio power P_{\min} for various radiotelescopes and observing times as a function of distance to the source: the MWA with observing times of 1 h, 1 day and 1 month (solid lines from top to bottom, Loeb & Zaldarriaga (2007)), the Green Bank Telescope with $\Delta\nu = 1$ Hz and observing time of 20 s (red dotted line) and the FAST with $\Delta\nu = 1$ Hz and observing time of 20 s and 1 h (green dotted line, from top to bottom). The blue line delineates the power per solid angle of military radars, and the intersection with the lines delimitates the maximum distance for a civilization to be detected by the telescope on Earth.

radiotelescope which is part of the Breakthrough Listen Project dedicated to SETI, and the Five hundred meter Aperture Spherical Telescope (FAST) which consists of a fixed 500 m dish with a collecting area 25 times bigger than the GBT and the MWA.

The MWA should be able to detect an ET signal up to distances of 25 pc with 1 month of observing time, the GBT up to distances of 12 pc with 20 s of observing time, the FAST up to 60 pc with 20 s and up to 220 pc with 1 h of observing time. We will calculate how many extraterrestrial civilizations generated by the simulations are within those limits.

Models

Human history hypothesis

An extraterrestrial civilization may not last forever. A civilization can die due to the lack of resources (e.g., food, water), overpopulation, or wars, among other factors. We calculated the probability of survival based on the history of civilizations on Earth. Examining some of the early civilizations they seem to have a fixed lifetime of about 1000 years (Blaha 2007), those civilizations and lifetimes are shown on Table 2.

Even though the end of those civilizations did not mean the end of the human race, we are studying the lifetime of civilizations not the specie itself. The collapse of an ancient civilization did not impact globally as the civilizations were more independent one from another. Today, the collapse of a technological civilization or a bad decision by one country (e.g., start a nuclear war) could create a global catastrophe, so the

Table 2. Examples of early civilizations and their lifetimes (adapted from Blaha 2007)

Civilization	Lifetime (years)
Sumerian	1100
Classical Mayan	1123
Moche Civilization	1150
Caral Civilization	900
Egyptians	934
Souther Nubia: Kingdom of Kush	1004
Mauritania and Mali	950
Zimbabwe	1000
China: Yellow River Civilization	1083
Japan	846
Anatolia	1500

collapse of a civilization could mean the end of the human species.

The probability that a ‘vulnerable’ intelligent civilization survives long enough to become ‘advanced’ was calculated as the average of the ratio of the individual civilizations lifetime to the summation of all civilizations lifetime ($t_{\text{civ}} = 9000$ years; Kapitza 2010), giving a result of 11% chance of surviving. Other approximations to this factor exist, such as the ‘sustainability solution’ (Haqq-Misra & Baum 2009), which relates the probability of survival with the speed of its growth, or the consideration of the physical limits (‘light cage limit’, McInnes 2002).

The ‘Tortoise and Hare’ hypothesis

The ‘Tortoise and Hare’ hypothesis was introduced by Forgan (2009). It proposes that civilizations that arise too quickly are more susceptible to self-destruction, and those that take longer to emerge are more likely to survive. The probability of self-destruction was parametrized by Forgan as:

$$P_{\text{destroy}} = \frac{t_0}{t_{\text{int}}}, \tag{15}$$

where $t_0 = N_{\text{stages}}t_i$ is the minimum time for life to evolve in the planet (when $N_{\text{resets}} = 0$).

Most of the Drake equation factors affect proportionally the results, as it has been stated in several sections of this work. On the other hand, for the life algorithm it is harder to predict the dependence of the parameters in the generation of life. We ran the simulations with slightly different parameters values to better understand how our model depends upon these parameters. For that, we took the Human History Hypothesis as the general model, and then we ran four cases with modified parameters. For the first two cases, we changed the number of stages needed for life to evolve to an intelligent civilization (N_{stages}), one with four steps as mean and another with eight steps (cases S4 and S8, respectively). In the second two cases, we changed the number of resets (N_{resets}), one with three resets and one with seven resets (cases R3 and R7, respectively). A summary of the parameters used are presented in Tables 3 and 4.

Table 3. *Parameters used in the Human History Hypothesis*

Case	Parameter	Mean	Standard deviation
All	t_i	0.8	0.25
All	t_{adv}	2.5×10^{-4} Gyr	1.0×10^{-4} Gyr
General	N_{stages}	6	1
General	N_{resets}	As equation (11)	
S4	N_{stages}	4	1
S4	N_{resets}	As equation (11)	
S8	N_{stages}	8	1
S8	N_{resets}	As equation (11)	
R3	N_{stages}	6	1
R3	N_{resets}	3	
R7	N_{stages}	6	1
R7	N_{resets}	7	
Case	Parameter	Value	
All	P_{life}	1 (if all criteria met)	
All	P_{adv}	0.11	

Table 4. *Parameters used in the Tortoise and Hare Hypothesis*

Parameter	Mean	Standard deviation
N_{stages}	6	1
N_{resets}	As equation (11)	
t_i	0.8	0.25
t_{adv}	2.5×10^{-4} Gyr	1.0×10^{-4} Gyr
Parameter	Value	
P_{life}	1 (if all criteria met)	
P_{adv}	as equation (12)	

Results and discussion

In Table 5, we show the statistics for the galactic model. The results show that 1.22% of Sun-like stars host an Earth-size planet (N_{\oplus}/N_{stars}), 5.58% of those Earth-size planets are in the habitable zone, so 0.33% of Sun-like stars harbour an Earth-like planet in the habitable zone. Figure 7 shows the fraction corresponding to each size of planets; 26% are Earth-size (1–1.6 R_{\oplus}), 32.5% are Super-Earth (1.6–2.5 R_{\oplus}), 35.5% are Neptune-size (2.5–6 R_{\oplus}) and 6% are Jupiter-size (6–16 R_{\oplus}).

It has to be considered that our model is only based on statistics from the raw Kepler data, as the goal of this study is to observe the relative tendency of the results as the observational data improves. Estimations made by other authors (e.g., Petigura *et al.* 2013) predict a higher fraction of Earth-like planets orbiting in their habitable zones (22%) since they corrected for instrumental limitations and observational biases.

Human history hypothesis

For the general case, around 51% ($N_1/N_{PHZ\oplus}$) of the present Earth-like planets in the HZ have primitive life. This supports the hypothesis that simple life is common in the Universe whenever the habitability criteria are met. The model predicts that there should be around 450 ‘vulnerable’ intelligent civilizations and 2600 advanced civilizations coexisting in the Milky Way at this moment. The reason there are more advanced than ‘vulnerable’ civilizations is because the time needed to

Table 5. *Statistics for the galactic model*

Variable	Definition	Mean	Standard deviation
N_{stars}	Number of stars	3.97×10^8	5434
$N_{planets}$	Number of planets	1.88×10^7	4067
$N_{HZplanets}$	Number of planets in the HZ	273 029	621
	Number of Earth-size planets	4.88×10^6	908
	Number of Earth-size planets in the HZ	70 985	231
	Number of planets in the HZ today	70 581	237

evolve from a vulnerable to an advanced civilization is much smaller than the time needed to evolve from primitive life to a vulnerable civilization. Also, an advanced civilization can survive forever while the ‘vulnerable’ one may destroy itself (N_3). Around the 7.7% of the life-hosting planets are inhabited by intelligent civilizations. This means that the biggest bottleneck is the progression from simple life to intelligence. As we see in Fig. 8, in most cases, life takes around 6 Gyr to evolve from simple to intelligent. Integrating the curve we obtain that life on the Earth evolved to intelligence faster than 85% of the total intelligent civilizations. This scenario supports the idea that we have not been contacted by a superior intelligent ET civilization because we are one of the first intelligent civilizations of the Galaxy. The next great bottleneck is the progression from ‘vulnerable’ to advanced civilization. Sagan & Shklovskii (1966) speculated that technological civilizations will either destroy themselves or master their self-destructive tendencies and survive for billion-year timescales.

Table 6 shows the different cases for this hypothesis to see how some parameters affect the results. Starting with the modification in the number of evolutionary steps, the number of planets with primitive life (N_1) decreased by 24% for S4 and increased 23% for S8. The number of ‘vulnerable’ civilizations (N_2) had a small variation, increasing by 2.2% for S4 and decreasing by 0.4% for S8. The number of self-destroyed civilizations (N_3) increased and decreased by 30% in S4 and S8, respectively. Lastly, the number of advanced civilizations (N_4) increased and decreased by 35% in S4 and S8, respectively. Figure 8 shows that for S4 the curve shifts to the left and for S8 shifts to the right. S4 is centred around 4.5 Gyr and S8 is centred around 8.2 Gyr. For the cases where the number of reset events changes, the main effect is on the number of biospheres which are annihilated (N_{-1}), decreasing by 40% with two less reset events (R3) and increasing 26% with two more resets (R7).

In general, the number of evolutionary steps has a greater influence on the time needed to develop an intelligent civilization than the number of reset events.

The Tortoise and Hare hypothesis

The results for the Tortoise and Hare Hypothesis are shown in Table 7. It can be seen that the difference between the

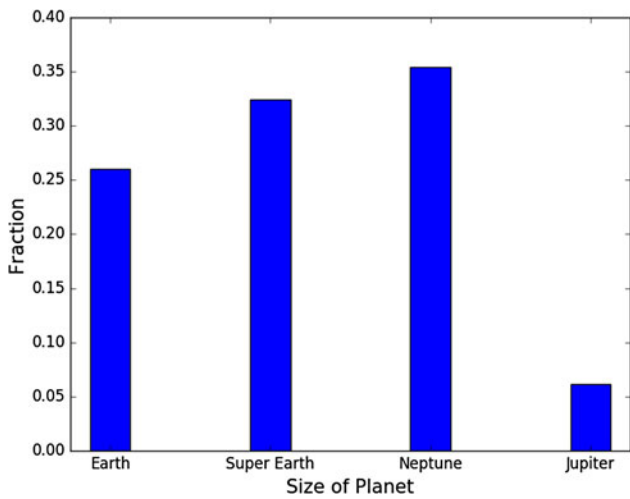


Fig. 7. Fraction of planets depending on their size: Earth-size planet (1–1.6 R_E), Super-Earth (1.6–2.5 R_E), Neptune-size (2.5–6 R_E) and Jupiter-size (6–16 R_E).

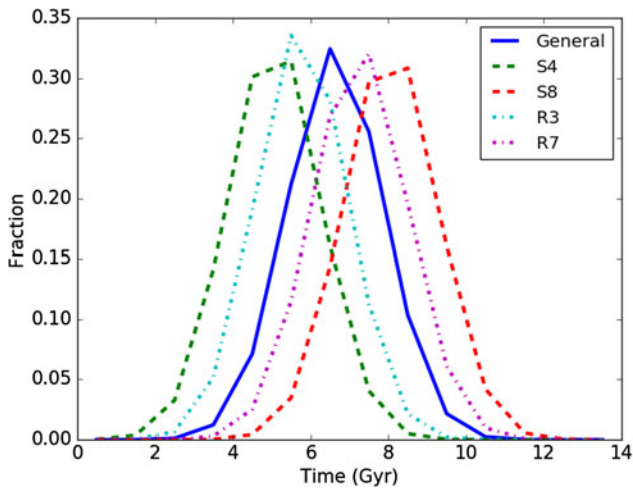


Fig. 8. Time needed for a life hosting planet to develop intelligent life. The five cases for the Human History Hypothesis are shown: general case (blue line), four steps case (S4, green dotted line), eight steps case (S8, red dotted line), three resets case (R3, cyan dotted line) and seven resets case (R7, purple dotted line).

hypothesis affects the evolution of life once primitive has been established. More than twice as many planets with primitive life evolve to host vulnerable civilizations and these, in turn, are 20% less likely to self-destruct. Consequently, the Tortoise and Hare hypothesis produces approximately three times the number of advanced civilizations compared with the Human History hypothesis.

According to both models, 85% of the civilizations that have existed in the Galaxy are ‘detectable’ (their signals reach the Earth). The closest detectable civilization is 110 ± 35 light years away from the Earth, but the closest non-detectable civilization is 33 ± 10 light years away. Observing for 1 month with the MWA radiotelescope we should be able to detect one civilization, translating to a probability of $\sim 10^{-3}$, but

Table 6. Statistics from the Human History Hypothesis

Variable	General	S4	S8	R3	R7
N_{-1}	7544±76	7513±56	7618±69	4542±77	9512±79
N_1	35 705 ±197	27 118 ±124	43 783 ±271	32 224 ±185	38 212 ±203
N_2	451±15	464±13	453±23	476±12	426±18
N_3	24 706 ±175	32 228 ±107	17 428 ±127	30 415 ±170	20 765 ±153
N_4	2594±49	3467±52	1683±32	3249±70	2144±42

See Table 1 for subindex information.

Table 7. Statistics from the Tortoise and Hare Hypothesis

Variable	Mean	Standard deviation
N_{-1}	7524	100
n_0	1.87×10^7	4161
N_1	35 642	224
N_2	1058	42
N_3	19 170	103
N_4	7518	94

See Table 1 for subindex information.

with less observation time we should not be able to detect any. The Green Bank telescope, which is currently the biggest radiotelescope dedicated to SETI work, would not be able to detect an ETI signal with the 20 s sample time assigned. The FAST radiotelescope from China raises expectations of detecting an ET signal, with a probability of detecting ET civilizations of $\sim 10^{-2}$ (4 ± 1 civilizations) and $\sim 10^{-1}$ (37 ± 6 civilization) with 20 s and 1 h of observation time, respectively. A similar study for the SKA (Square Kilometre Array) was done by Forgan & Nichol (2011) and they showed that the probability of civilizations accidentally detecting each other was $\sim 10^{-7}$.

We have applied the results to the data from the Kepler Mission FOV. This field comprises about 223 000 stars, from which about 136 000 are estimated to be in the main sequence (Monet 1996). Comparing the numbers, there should be six Earth-like planets in the HZ orbiting main sequence Sun-like stars within Kepler’s FOV. According to the Human History Hypothesis results, there is a high probability of finding simple life on three of them, but a probability of only a 4.3% of finding an intelligent civilization. On the other hand, applying the results of the Tortoise and Hare Hypothesis, there should be three planets with primitive life and a 12% probability for the existence of an intelligent civilization. At the time of writing, there is only one confirmed exoplanet in the habitable zone orbiting a G2 star (Jenkins *et al.* 2015).

Conclusions

We have estimated the number of habitable planets within the SGR and the probability of those planets for hosting life from primitive to advanced civilizations using a simple galactic model, updated exoplanet data, conservative habitability criteria, and a hard step scenario to simulate the evolution of life.

Our model predicts that about 55% of the Earth-like planets in the HZ are inhabited, 51% by primitive life and 4% by an intelligent civilization. According to our general model, most of the life in the Galaxy takes more time to evolve to intelligent than Earth's life.

We showed that the life algorithm is very consistent, as changing some parameters do not affect the final results by more than 35%.

The model has limitations due the incompleteness of the planetary observational data and simplifications in the galactic model, such as not considering chemical evolution of the Galaxy and its consequences in the generation of Earth-like planets. The weak parameters are very difficult to estimate accurately; any changes in them proportionally affect our final result.

We also predict that there should be six Earth-like planets in the HZ within the Kepler FOV, which is consistent with the present data. The probability of finding primitive life is very high on those planets, as three of them could have it. However, the probability of finding technological life in that region is only 4.3% (0.26 planets!)

Our results support two possible solutions for the Fermi Paradox: (1) We are the only technological civilization in our Galaxy or one of the few, since most of the life in our model is incapable of developing technology to communicate outside their planets. (2) We cannot detect other civilizations because, as we showed, the probability of detecting human-like technological civilizations is low ($\sim 10^{-1}$) with our current instruments and observation plans.

Even though the probability of finding technological civilizations seems low, it is not minuscule. More studies have to be done to discuss the probability of success of the current SETI projects, more observation time or the participation of more and bigger radiotelescope could be necessary.

It is important to highlight that this is only a model, and the results should not be taken as absolute values but as relative trends as the input parameters improve.

Further studies are required to improve the model. The astrophysical parameters are ever better constrained frequently, especially the exoplanet data. Future missions, such as PLATO (Catala et al. 2010) or CHEOPS (Claudi et al. 2004), will provide more details of the properties of the exoplanets and their habitability characteristics. Biological parameters are the main problem for doing this type of models, by finding life anywhere outside our planet we could make fewer assumptions and have more precise results.

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