The Fermi paradox: Impact of astrophysical processes and dynamical evolution

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Abstract

The Fermi paradox has given rise to various attempts to explain why no evidence of extraterrestrial civilisations was found so far on Earth and in our Solar System. Here, we present a dynamical model for the development of such civilisations, which accounts for self-destruction, colonisation and astrophysical destruction mechanisms of civilisations including gamma-ray bursts, type Ia and type II supernovae as well as radiation from the supermassive black hole. We adopt conservative estimates regarding the efficiency of such processes and find that astrophysical effects can influence the development of intelligent civilisations and change the number of systems with such civilisations by roughly a factor of 2; potentially more if the feedback is enhanced. Our results show that non-equilibrium evolution allows for solutions in-between extreme cases such as "rare Earth" or extreme colonisation, including scenarios with civilisation fractions between $10^{-2}$ and $10^{-7}$. These would imply still potentially large distances to the next such civilisations, particularly when persistence phenomena are being considered. As previous studies, we confirm that the main uncertainties are due to the lifetime of civilisations as well as the assumed rate of colonisation. For SETI-like studies, we believe that unbiased searches are needed considering both the possibilities that the next civilisations are nearby or potentially very far away.

Introduction

Our Universe is 13.76 Gyrs old [Komatsu et al.(2011)], and estimates suggest that our Galaxy could be colonised by advanced civilisations on the Fermi-Hart timescale [Hart(1975), Tipler(1980)] of

$$t_{FH} = 10^6 - 10^8 \text{ years}, \quad (1)$$

taking into account the size of the Milky Way and rough estimates for the travel time between stars. The fact that it did not happen or at least that we are not aware of any evidence for it is generally referred to as the Fermi paradox, expressed via the question "Where is everybody?" over a conversation at lunch.

A very large range of possible solutions have been suggested for this problem (see Cirkovic(2009) for a relatively recent review), which can be grouped into some typical classes of solutions: a) The "rare Earth"-type solutions going back to Ward & Brownlee(2000), which basically argues that the formation of intelligent, advanced civilisations requires so rare and specialized conditions that it could effectively happen only once in our Galaxy or even once in our Universe. b) Catastrophic solutions that basically suggest the self-destruction of advanced civilisations before they can start the colonisation process, considering options like Nuclear War, misuse of biotechnology, artificial intelligence or others Cirkovic(2004), Bostrom & Cirkovic(2008). c) The possibility that advanced civilisations were actually here, but the expansion process rapidly moves forward and leaves behind an uncolonised wasteland Stull(1979), Finney & Jones(1985). d) The class of solipsist solutions Sagan & Newman(1983), who suggest that the reason for the apparent absence of extraterrestrial civilisations is more related to the limits of our observations both of the Solar System as well as the Milky Way galaxy. A variant of this includes the zoo hypothesis Ball(1975) which suggests that advanced extraterrestrial civilisations would rather avoid direct contact or visible manifestations of themselves, but rather observe us from the outside, for reasons of ethics, prudence or practicality Deardorff(1987).
Of course, while explanations based on social dynamics of advanced civilisations can be a possibility, it is something out of the reach of practical investigations. On the other hand, the history of science on the long term has told us that our place in the Universe is not particularly special; we had to abandon the geocentric and the heliocentric theory, and modern cosmology suggests that the Universe is homogeneous and isotropic at least on large scales. In this light, it is worth repeating the argument given by [Kinouchi(2001)], which basically concerns independent civilisations on Earth. Very similar to the Fermi hypothesis, one could calculate the time scale it requires for a nation to establish contact with everybody on Earth, and independent of the details on how it is done, it surely would be feasible within less than 100 years. The Brazilian government estimates that there are two hundred not contacted populations inside Amazonia, and there are many lost islands in Indonesia, roughly 6000 of them inhabited but without contact to civilisation. If any member of such a not contacted population was to ask Fermi’s question, they could easily conclude that no other human populations exist on Earth, since otherwise they should have been contacted by them. Other arguments to consider include considerations about the sustainability of an exponential expansion [Haqq-Misra & Baum(2009)], or potential problems due to the limited speed of light, potentially prohibiting efficient communication over very large scales. The Fermi paradox thus needs to be regarded with a grain of salt, to which many possible factors may contribute.

Particularly, it is important to say that classic estimates based on e.g. the Drake equation [Burchell(2006)] include, in addition to large uncertainties, many implicit assumptions, such as the suggestion that an equilibrium state has been effectively reached. Which may or may not be the case, and some of the corresponding limitations were already pointed out by [Cirković(2004)]. Dynamical generalizations of the Drake equation have been explored e.g. by [Panov(2018)] and the age distribution of potential intelligent life in our Milky Way has been estimated by [Legassick(2015)] taking the astrophysical formation of the Galaxy into account. More recently, a stochastic formulation of the Drake equation as a balance of birth-death processes was presented by [Kipping(2021)].

Such dynamical generalisations make sense, as the Universe and our Galaxy themselves are dynamically evolving, the number of habitable systems is growing over time, but there are also astrophysical processes that could have very destructive impacts on the development of complex forms of life, particularly at earlier times in the Universe, which can only be taken into account within dynamical models. Already [Amnis(1999)] suggested that astrophysical events like gamma-ray bursts could have a large destructive impact on our Galaxy, and potentially prohibit the formation of civilisations on very large scales. [Galante & Horvath(2007)] estimated that such events could even affect planetary systems more than 150 kpc from the original event. [Cirković & Vukotić(2008)] thus concluded that these or other events could lead to a global reset and in case such events were very common in the early Universe, may simply have prohibited the development of intelligent civilisations until recently. These models are nonetheless highly simplified, as gamma-ray bursts are highly beamed rather than spherical explosions, thus affecting only a smaller part of the galaxy.

In addition to gamma-ray bursts, there are other explosive events in our Galaxy, in particular the type Ia and type II supernovae, whose effects on astrobiology were already estimated e.g. by [Gowanlock et al. (2011)]. Particularly in the first two billion years, radiation from the activity of the supermassive black hole in our Galaxy could have affected the development of life, particularly in the inner region, the central few kiloparsecs [Balbi & Tombesi(2017)].

In this paper, we aim to explore the population dynamics of advanced extraterrestrial civilisations, taking into account astrophysical constraints, the dynamical evolution within a non-equilibrium model, the impact of astrophysical events such as black hole activity, gamma-ray bursts and supernova explosions, as well as the possibility of colonisation and auto-destruction of civilisations via catastrophic events, which we parametrise due to the uncertainties. In the following, we will present first estimates based on the Drake equation, and then introduce a non-equilibrium model that includes the above-mentioned processes. Subsequently we present the results of the model and discuss the astrobiological implications.

The Drake equation: first estimates

The Drake equation aims to estimate the number of communicating civilisations and is given, in its original form, as

\[ N_{CC} = R_s f_p n_e f_l i f_c L, \]

(2)

where \( R_s \) is the formation rate of stars in our galaxy averaged over all times, \( f_p \) the fraction of stars that host planetary systems, \( n_e \) the average number of planets per system suitable for life, \( f_l \) is the fraction of such planets where intelligent life has developed, \( f_c \) is the fraction of such planets where life has reached the communicative phase, and \( L \) is the average duration of the communicative phase.

Some of these parameters are very well-known; we have a star formation rate of \( \sim 1.9 \, M_\odot \text{ year}^{-1} \) [Twarog(1980), Meusinger(1991), Chomiuk & Povich(2011)]. As shown by the work of [Kroupa & Weidner(2003)], the initial mass function of stars is peaked in the low-mass regime, such that the average number of stars per one solar mass is about 2. This implies the formation of roughly 4 stars per year. In the Milky Way galaxy, overall a rather quiescent evolution seems to have taken place over its history [Kennicutt & Evans(2012)]. To reproduce the \( \sim 10^{11} \) stars in the Milky Way today, one needs to assume on average a rate \( R_s \sim 10 \text{ year}^{-1} \) for the last 10 billion years [Prantzos(2013)].

We focus here predominantly on planets in the super-Earth regime with 2 up to 10 Earth masses, as defined by [Stevens & Gaudi(2013)]. An upper limit on their abundance can be obtained from the analysis of [Mayor et al.(2011)], who estimate the fraction of planets with less than 30 Earth masses as about 10%. Another estimate has been made by [Selsis(2007)], requiring stars to be sufficiently long-lived for the development of complex life forms (with main-sequence lifetimes larger than 4.5 Gyr, and thus masses less than 1.1 \( M_\odot \)) while having sufficiently high masses to have habitable zones outside the tidally locked regions, where always the same side of the planet would be exposed to radiation from the star. Based on these considerations, they arrived at a fraction of about 10%. We also assume here
that within the habitable zone, we will only have about one planet per system. As these are independent requirements that need to be simultaneously fulfilled, we may then estimate \( f_p n_c \sim 0.1 \cdot 0.13 = 0.013 \) [? see also] for a similar discussion Prantzos 2013.

From astrophysical considerations, we thus arrive at a rate \( R_{\text{astro}} = R_s f_p n_c \sim 0.052 \) habitable planets per year. We can further group the biological terms, \( f_b = f_i f_c \), describing the fraction of those planets where intelligent life developed. The only reference system we can consider here is Earth, which has an approximate total age of 4.5 Gyrs, while the first hominids appeared about 6 million years ago. Based on these considerations, one could estimate \( f_b \sim 0.606 \times 10^{-3} \), which might be considered as an upper limit. To estimate the fraction of planets where life has reached the communicative phase, again our only reference point is Earth, where radio signals exist since roughly the 1950s. Based on this consideration, one might infer a possible minimum value of the corresponding fraction, of course under the assumption that typical life will behave similarly as on Earth, which would be \( f_c, \text{min} \sim 7 \times 10^{-6} \). On the other hand, this fraction may also be considerably larger, and also the human society may keep communicating for a considerable amount of time. With the average duration of the communicative phase \( L \), we can make an improved estimate \( f_c \sim 6 \times 10^{-6} \) years, implying \( f_c L \sim 6 \times 10^5 \) years.

Putting the numbers together, we thus obtain

\[
N_{\text{CC}} \sim 8.7 \times 10^{-12} \left( \frac{L}{\text{years}} \right)^2 .
\]  

(3)

The number of communicating civilisations thus depends very strongly on their assumed lifetime, and of course it is still important to note that it would require a very advanced civilisation to detect the radio signals from Earth over a large distance. Nonetheless, for lifetimes of \( L \sim 10^6 \) years, we could then expect \( N_{\text{CC}} \sim 9 \) communicating civilisations in our Galaxy.

A very relevant uncertainty can be removed, however, if we employ a modified version of the Drake equation where we aim to estimate the total number of civilisations, irrespective of whether they are communicating or not. We denote the number of total civilisations as \( N_c \). It can be estimated by removing the factor \( f_c \) from the Drake equation and by replacing the lifetime \( L \) of the communicative phase with the total lifetime \( L_{\text{tot}} \) of an average civilisation. We obtain the following estimate:

\[
N_c \sim 5.2 \times 10^{-5} \left( \frac{L_{\text{tot}}}{\text{years}} \right) .
\]  

(4)

If we take \( L_{\text{tot}} \sim 10^7 \) years, which can be easily justified with the timescale since hominids are living on Earth, we arrive at \( N_c \sim 520 \) civilisations.

These estimates in particular do not yet take the possible process of colonisation into account. While our civilisation has not started such a process yet, it is worth noting that Earth formed only 4.5 Gyrs ago, and other civilisations may have formed even Gyrs before ours. A more complete model thus needs to take this process into account. We further point out another important limitation of the Drake equation: being tied to the star formation rate, it assumes civilisations to exist only on planets around recently formed stars. It is not obvious that this assumption is correct and even in the complete absence of current star formation, it would be conceivable that extraterrestrial civilisations exist on planets that formed billions of years ago. Another improvement of a dynamical framework is thus that it allows to take both the recently formed planets plus the already existing ones into account.

### A non-equilibrium model

We now go beyond the Drake equation and present a dynamical non-equilibrium model which takes into account the process of colonisation as well as astrophysical destruction mechanisms of civilisations. Within this framework, we will consider the number of habitable planets \( N_h \) which provide conditions for life to develop though it has not developed yet. \( N_l \) denotes the number of systems where simple forms of life have developed, \( N_a \) the number of systems including animal life forms on land and finally \( N_c \) the number of systems with civilisations. The total number of habitable planets at a given time is thus given as \( N_h + N_l + N_a + N_c \), which is increasing over time due to ongoing star formation.

Fig. 1. Illustration of the dynamical model described via Eqs. A symbols legend is also reported for clarity.
The evolution equations in our model are given as (see also Fig. 1 for an illustration)

\[
\begin{align*}
\dot{N}_h &= R_{\text{astro}}(t) - \epsilon_i N_h - \epsilon_{\text{col}} N_c N_h/N, \\
\dot{N}_l &= \epsilon_f N_h - \epsilon_{\text{col}} N_l + \epsilon_{\text{ast}, a}(t) N_a - \epsilon_{\text{ol}} N_c N_l/N, \\
\dot{N}_a &= \epsilon_{\text{col}} N_l - \epsilon_c N_a + \epsilon_d N_c + \epsilon_{\text{ast}, c}(t) N_c \\
&\quad - \epsilon_{\text{ast}, a}(t) N_a - \epsilon_{\text{col}} N_c N_a/N, \\
\dot{N}_c &= \epsilon_c N_a - \epsilon_d N_c + \epsilon_{\text{col}} N_c (N_h + N_l + N_a)/N \\
&\quad - \epsilon_{\text{ast}, c}(t) N_c,
\end{align*}
\]

where \( N = N_h + N_l + N_a + N_c \) is the total number of systems, \( R_{\text{astro}}(t) \) is the astrophysical formation rate of habitable planets and \( \epsilon_i, \epsilon_c, \epsilon_{\text{col}}, \epsilon_d, \epsilon_{\text{ast}, c} \) and \( \epsilon_{\text{ast}, a} \) denote various efficiency parameters that are introduced in further detail below.

First, we aim to derive a time-dependent model for the formation rate of habitable planets. As the evolution of star formation in the Milky Way overall was rather quiescent [7, e.g.], Kennicutt 2012, we assume only a moderate time-dependence, following an exponential decay over a long timescale of \( \sim 5 \) Gyrs. We choose our normalization such that over a timescale of 10 Gyrs, the same number of systems will be produced with the time-averaged rate we adopted in the Drake equation above. We then have

\[
R_{\text{astro}}(t) = 0.20 \times 10^9 \text{ Gyr exp} \left( -\frac{t}{5 \text{ Gyr}} \right). \tag{9}
\]

Here \( t \) is the time coordinate in our model, which is chosen such that at the present day we have \( t = 0 \).

As initial conditions, we assume here that \( N_h = N_l = N_a = N_c = 0 \), so all the systems form via the production term \( R_{\text{astro}}(t) \). \( \epsilon_i \) is the efficiency parameter describing the transition from a habitable planet to a planet with simple forms of life (cells or bacteria), which we parametrise as \( \epsilon_i = T_i^{-1} \). \( T_i \) is the characteristic timescale for a simple form of life to develop. We adopt here \( T_i = 10^9 \) years, comparable to the time it took for the first life forms to develop on Earth. The term \( \epsilon_c \) describes the transition from a planet with simple forms of life to planets with animal-type forms of life that live on land. We consider this as a particularly important intermediate stage that was a precondition for the subsequent development of civilisations. We adopt here \( \epsilon_c = T_c^{-1} \), with \( T_c \sim 3 \) Gyr considering the evolutionary time on Earth.

For the development of intelligent life and civilisations, similar as [Annis(1999)], we assume that roughly \( 0.1 \) Gyr are required to develop sufficiently complex base classes of land-dwelling creatures, and subsequently another \( 0.1 \) Gyr to develop intelligence once sufficiently complex base classes were being established. For the parameter \( \epsilon_d \) describing the transition to intelligent life and civilisations, we thus adopt \( \epsilon_d = T_d^{-1} \), with \( T_d \sim 0.2 \) Gyr.

**Astrophysical destruction mechanisms**

We now consider astrophysical effects that can potentially destroy civilisations and even affect animal life. We parametrise the effect on civilisations via \( \epsilon_{\text{ast}, c}(t) = \epsilon_{\text{AGN}}(t) + \epsilon_{gb}(t) + \epsilon_{SNIa}(t) + \epsilon_{SNII}(t) \), including feedback from the galactic supermassive black hole, gamma-ray bursts as well as type Ia and type II supernovae. The effect of such feedback on animal life is incorporated as well, which we parametrise via \( \epsilon_{\text{ast}, a} = a \epsilon_{\text{ast}, c} \) with \( a \sim 0.25 \).

The parameter \( a \) is of course very uncertain, though we consider here that more simple types of small animals should have higher chances to potentially survive catastrophic events.

For up to the first two billion years in our Galaxy, the supermassive black hole has likely been active, and we parametrise the effect of its feedback following [Babbi & Tombesi(2017)], who calculated that it would very severely affect planetary atmospheres and ecosystems up to \( 3 \) kpc from the center of the Galaxy.

Considering a typical size of \( 30 \) kpc of the Galactic disk, the fraction of systems affected via the feedback thus amounts to \( p_{\text{AGN}} \sim 0.01 \). We adopt a characteristic timescale of \( T_{\text{AGN}} \sim 10^{-3} \) Gys for the feedback events from the black hole, and thus arrive at an efficiency \( \epsilon_{\text{AGN}} = p_{\text{AGN}}/T_{\text{AGN}} \) during the first 2 Gyrs, and subsequently \( \epsilon_{\text{AGN}} = 0 \).

For gamma-ray bursts, it is harder to make precise estimates, as their explosions are not spherical but highly beamed. In principle there are uncertainties given their absolute event rates, as they can only be detected from Earth if Earth falls into the beam of the gamma-ray burst. In case of smaller beams, the event rate is thus higher than typically estimated, and smaller for larger beams. Regarding the overall efficiency of the feedback, this uncertainty nevertheless is balanced out as a higher event rate would then correspond to an accordingly smaller part of the Galaxy affected by the event. For simplicity, what we adopt here is the estimate by [Melott et al.(2004)], who assume that planetary systems would be strongly affected within \( 3 \) kpc of the gamma-ray burst, thus corresponding to a fraction of \( p_{gb} = 0.01 \) of the Galactic disk. Again following [Melott et al.(2004)], we assume that currently in the Universe, such events occur roughly at a period of \( P_{\gamma} = 170 \) Myrs. This rate should be expected to evolve over time, and we assume it to decay over a characteristic timescale of \( t_{\gamma} \sim 5 \) Gyr, consistent with cosmological observations [Bromm & Loeb(2002)]. We thus arrive at the following event rate

\[
\nu_{\gamma}(t) = \nu_0 \exp \left( -\frac{t}{t_{\gamma}} \right) \tag{10}
\]

with \( \nu_0 = 1/P_{\gamma} \) and the corresponding efficiency parameter is thus given as

\[
\epsilon_{gb}(t) = p_{gb} \nu_{\gamma}(t). \tag{11}
\]

For the rate of type Ia supernovae, we adopt the estimated rate of \( \nu_{\text{SNIa}} = 4 \times 10^{-3} \) yr\(^{-1}\) from [Gowanlock et al.(2011)] for the last billion years, consistent also with [Meng & Yang(2010)]. The type Ia supernova rates are expected to evolve as the Galactic star formation rate, though with a delay time of 1 Gyr due to stellar evolution effects. We assume here a similar decay law as for the gamma-ray bursts, though with a different frequency. For the type Ia supernova, [Gowanlock et al.(2011)] derived a sterilization radius of 19 pc, corresponding to a fraction \( p_{\text{SNIa}} \sim 4 \times 10^{-7} \) of the Galactic disk. Accounting for the delay time of 1 Gyr, we write

\[
\epsilon_{\text{SNIa}}(t) = p_{\text{SNIa}} \nu_{\text{SNIa}} \exp \left( -\frac{t - 1 \text{ Gyr}}{t_{\gamma}} \right). \tag{12}
\]

For the type II supernovae, we recall the sterilization radius derived by [Gowanlock et al.(2011)], corresponding to 8 pc or a fraction of \( p_{\text{SNII}} = 0.008^2/30^2 \sim 7 \times 10^{-8} \) of the Galactic
developed above by employing the SCIPY’s SOLVE_IVP Python function, an implicit multi-step variable-order BDF solver. The system of equations is integrated from time $t = -10$ Gyrs until $t = 0$, in a logarithmically spaced grid of 100 points. We recall that we only model here the habitable systems, so roughly a fraction of $f_{p} n_{c} \sim 0.013$ of all systems, as discussed in our estimates regarding the Drake equation. As a reference model, we adopt the parameters $T_{d} = 10^{-3}$ Gyrs and $N_{\text{new}} = 10^{3}$ to show the results of the model in a specific case, and we also show how it is sensitive to changes and variations in these parameters. We summarize the main input parameters for our reference model in Table 1.

Within our reference model (see Fig. 2), in general a significant number of planetary systems builds up within the first billion years, where the formation rate of these systems is enhanced by a factor $\epsilon^{2} \sim 7.3$, allowing to form roughly the same number of systems as in the subsequent 9 Gyrs. These systems are habitable and so simple life starts to develop, and after roughly 2 Gyrs there are more systems with simple life than without. After roughly 5 Gyrs, the number of systems with animal life is larger than the number of systems with simple life. The number of civilisations grows steadily, and reaches about $10^{7}$ after 10 Gyrs, thus corresponding to a fraction of 1% of all planetary systems. The number of civilisations is thus considerably larger than based on the estimate in the Drake equation. The main reason is that the Drake equation only considers very recently formed stellar systems, as it is tied to the star formation rate, and with a lifetime of the civilisations of the order of one million years, the time they stay in that phase is short compared to the age of the Universe. The dynamical model considered here on the other hand allows for the development of civilisations on all of the habitable systems, including those that previously harbored a civilisation that subsequently disappeared. Further, also the process of colonisation is taken into account, though still at a moderate level with $N_{\text{new}} = 1000$, which basically does not yet affect the evolution very much. An important effect that we see is that the number of civilisations keeps monotonically increasing and an equilibrium state has not been reached even after 10 Gyrs, and it is also not expected due to the continuously increasing number of available systems. This underlines in principle the importance of a non-equilibrium treatment for the modeling of such populations.

We now focus on the effect of the parameter $T_{d}$, as a potentially short lifetime of a civilisation is often considered as a possible solution towards the Fermi paradox, and we show what happens when this parameter is varied in Fig. 2. As expected, we find it to significantly affect the number of systems with civilisations, and so simple life starts to develop, and after roughly $9 \times 10^{9}$ years, where the formation rate of these systems is enhanced by a factor $\epsilon^{2} \sim 7.3$, allowing to form roughly the same number of systems as in the subsequent 9 Gyrs. These systems are habitable and so simple life starts to develop, and after roughly 2 Gyrs there are more systems with simple life than without. After roughly 5 Gyrs, the number of systems with animal life is larger than the number of systems with simple life. The number of civilisations grows steadily, and reaches about $10^{7}$ after 10 Gyrs, thus corresponding to a fraction of 1% of all planetary systems. The number of civilisations is thus considerably larger than based on the estimate in the Drake equation. The main reason is that the Drake equation only considers very recently formed stellar systems, as it is tied to the star formation rate, and with a lifetime of the civilisations of the order of one million years, the time they stay in that phase is short compared to the age of the Universe. The dynamical model considered here on the other hand allows for the development of civilisations on all of the habitable systems, including those that previously harbored a civilisation that subsequently disappeared. Further, also the process of colonisation is taken into account, though still at a moderate level with $N_{\text{new}} = 1000$, which basically does not yet affect the evolution very much. An important effect that we see is that the number of civilisations keeps monotonically increasing and an equilibrium state has not been reached even after 10 Gyrs, and it is also not expected due to the continuously increasing number of available systems. This underlines in principle the importance of a non-equilibrium treatment for the modeling of such populations.

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which changes essentially by the same factor. It is interesting to
note that even in the extreme case of $T_d = 1$ kyr, still roughly
$10^4$ civilisations are left, while in case of $T_d \sim 1$ Myr, almost all
of the systems include civilisations, with the fraction of systems
that harbors only animal life decreasing by more than an order of
magnitude at the end of the evolution.

We next consider the effect of varying the parameter $N_{\text{new}}$, i.e. the number of colonies a civilisation would create over a
timescale of 10 Gyrs. This in principle tells us already that this
effect will only be important if the lifetime of a civilisation will be
sufficiently large, i.e. we need to have

$$\frac{10 \text{ Gyr}}{N_{\text{new}}} < T_d$$  \hspace{1cm} (15)$$

for colonisation to be efficient. We will consider here parameters
$N_{\text{new}} = 10^3$, $10^4$ and $3 \times 10^4$ (see Fig. 4). The first case is our
reference scenario where we obtain about $10^7$ systems with civilisations, and we have $10 \text{ Gyr}/N_{\text{new}} > T_d$, so the process as noted
above is not yet efficient. For $N_{\text{new}} = 10^4$, we are at the limiting
case where $10 \text{ Gyr}/N_{\text{new}} = T_d$. At this point the colonisation
process contributes in a relevant way to form civilisations, and $N_c$
increases by roughly an order of magnitude (as essentially the
death of civilisations is compensated for). With $N_{\text{new}} = 3 \times 10^4$, we are at $N_c > 10^9$, so at this point almost all habitable planets
have colonies. A further increase of $N_{\text{new}}$ would thus not make a
relevant difference at the current time in the Universe, and in
principle not even for most of the past, as indeed a high level of
colonisation is then already reached after a few Gyrs.

An important part of our assessment further concerns the impact of astrophysical feedback mechanisms, such as radiation
from the supermassive black hole, gamma-ray bursts as well as
type Ia and type II supernovae on the evolution of civilisations and
the model in general. For this purpose, we show our models
with the astrophysical feedback implementation, without the feed-
back as well as a case where the feedback is artificially enhanced
by a factor of 10 in Fig. 5. The latter is done to account for
potential uncertainties, both regarding the astrophysical parame-
ters themselves, but also due to the uncertainties in their impact on
planetary systems. It is probably fair to say that we adopted here
somewhat conservative estimates of the impact of astrophysical
effects.

In spite of the uncertainties, one can probably say that these
parameters are nonetheless better constrained than $T_d$ or $N_{\text{new}}$, so it seems appropriate to vary them to a lesser degree. In spite of
this, we find that the astrophysical feedback influences the devel-
opment of civilisations by a relevant degree. In our reference case
as before, we find $N_c \sim 10^7$, which increases by roughly a factor
of 3 if feedback is being switched off. The increase is even larger
at earlier times where the frequency of supernovae and gamma-
ray bursts is still higher and the feedback thus more efficient.
We find here that particularly the type Ia supernovae and next
the type II supernovae are making a difference; gamma-ray bursts
affect a larger fraction of the galaxy but nonetheless are much less
frequent and thus overall less important. On the other hand, the
feedback by the supermassive black hole matters only in the first
two Gyrs where the civilisations in general are still building up
and the feedback overall is less relevant. We note that, in the case
we artificially increase astrophysical feedback by a factor of 10, the
number of civilisations decreases by a corresponding factor.

For a comparison of the different effects considered here, we
provide a summary plot in Fig. 6 showing the fraction of civil-
isations (with respect to all planetary systems, i.e. including the
factor $f_p n_c$), to show how the latter varies under different condi-
tions. Particularly, we find that a short lifetime of civilisations is
most effective in suppressing their abundance, but also enhanced
astrophysical destruction can bring down the fraction of civil-
isations. The efficiency of colonisation is very uncertain but can
bring up the number of civilisations by a very high degree. Astro-
physical feedback in general affects the number of civilisations by
roughly a factor of 3.

Discussion and conclusions

We have developed and presented a non-equilibrium model that
describes the emergence of civilisations, the process of coloni-
sation as well as their destruction via astrophysical feedback
mechanisms, including radiation from the central black hole in
In the context of the Fermi paradox, it currently appears that the corresponding effects are not strong enough to resolve it, but nonetheless they are a relevant factor for the modeling of the development of intelligent civilisations.

The two most uncertain parameters in the modeling of such civilisations are still their typical lifetimes as well as their colonisation rates, which potentially can vary by orders of magnitude. It is in principle thus unsurprising that they can lead to a similarly large variation in the results. What distinguishes our model from more simplified estimates is that it allows to treat and identify some intermediate cases, where small but nonetheless relevant fractions of intelligent civilisations exist within the Milky Way galaxy, and we have shown several cases here with outcomes in the range of $10^{-3}$ up to $10^{7}$, which correspond to fractions of $10^{-8}$ up to $10^{-4}$ of all planetary systems. These solutions are interesting as they are in-between the extreme cases of the "rare Earth" solutions with effectively one civilisation per galaxy, or the Fermi paradox where almost every habitable system should be colonised. The fractions are also low enough to still imply a significant distance of any such civilisations from Earth, particularly if additional effects such as persistence are taken into account [Klochuk2001]. Even in the regime where colonisation is not yet important, i.e. where the colonisation rate is lower than the death rate of civilisations, the estimates from our dynamical model imply much larger numbers of civilisations as compared to the Drake equation. This is due to the fact that in our dynamical model, these can form on all habitable stellar systems, while the estimates of the Drake equation are tied to the star formation rate and only consider the recently formed stars. It further implicitly assumes that each stellar system will develop a civilisation only once, while in our model it is feasible that a civilisation on a system develops, dies and later on on a new one forms. The number of civilisations overall is continuously increasing, essentially due to the continuous increase of habitable systems.

We note also some of the simplifications we had to make; particularly the timescales for the development of simple life, animal life and civilisations were only motivated from the development on Earth and are very approximate; unfortunately so far we do not have another reference point to assess i.e. the possible variation in these parameters. We also note that the development of animal or intelligent life may not necessarily be restricted to super-Earth type planets as assumed here, and other channels for the development of such lifeforms may exist for instance in the moons of giant or rogue planets as well [Avila et al. 2021]. The purpose of our work however was to provide a simple model and also to avoid speculation as much as possible, and thus to be rather conservative in our estimates.

In the context of SETI-like searches, of course one needs to obtain estimates not only for the number of civilisations, but also the number of communicating civilisations, which adds another degree of uncertainty, as we also do not know whether advanced civilisations will keep communicating or whether they might stop doing that, for reasons of security, energy efficiency or other types of considerations. Our results for the number of civilisations can of course be rescaled with any factor $f_c$ that appears well-motivated in a given context, though overall remains unknown.

Regarding SETI-like projects, it is difficult to derive firm conclusions, and we believe that such projects should be pursued with
an open mind, i.e. avoiding a priori assumptions on where other civilisations might be. Important discoveries can include the unexpected and a theory can only be validated or disproven via actual investigation. This should happen with as little bias as possible, considering both the possibilities of other civilisations (or their precursors) being close or distant.

Acknowledgement. DRGS and SB gratefully acknowledge support by the ANID BASAL projects ACE210002 and FB210003, as well as via the Millenium Nucleus NCN19-058 (TITANS). DRGS thanks for funding via Fondecyt Regular (project code 1201280). SB is financially supported by ANID Fondecyt Regular (project code 1220033).

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