

# The Temporal Aspect of the Drake Equation and SETI

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## Abstract

We critically investigate some evolutionary aspects of the famous Drake equation, which is usually presented as the central guide for the research on extraterrestrial intelligence. It is shown that the Drake equation tacitly relies on unverifiable and possibly false assumptions on both the physico-chemical history of our Galaxy and the properties of advanced intelligent communities. The importance of recent results of Lineweaver on chemical build-up of inhabitable planets for SETI is emphasized. Two important evolutionary effects are briefly discussed and the resolution of the difficulties within the context of the phase-transition astrobiological models sketched.

Keywords: Galaxy: evolution, extraterrestrial intelligence, history and philosophy of astronomy

## 1 Introduction

It is hard to deny that the Search for ExtraTerrestrial Intelligence (SETI) is one of the major scientific adventures in the history of humankind. At the beginning of XXI century it remains the oldest and perhaps the most fascinating scientific problem. However, the field is still largely qualitative and thus often not taken seriously enough. One of the attempts to overcome this circumstance is encapsulated in the famous Drake equation, developed by Frank Drake for the first SETI symposium in 1961.

The first problem any student of SETI faces is that there is no canonical form of the Drake equation. Various authors quote various forms of the equation, and it is in a sense dependent on what is the desired result of the analysis. We shall investigate the following form (e.g. Shklovskii and Sagan 1966; Walters, Hoover, and Kotra 1980):

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

while keeping in mind that other equivalent forms exist as well. In this expression, the symbols have the following meanings:

$N$  = the number of Galactic civilizations with whom communication is possible.

$R_*$  = mean rate of star formation in the Galaxy,

$f_g$  = fraction of stars suitable for supporting life,

$f_p$  = fraction of stars with planetary systems,

$n_e$  = number of planets per planetary system with conditions ecologically suitable for the origin and evolution of life,

$f_l$  = fraction of suitable planets where life originates and evolves into more complex forms,

$f_i$  = fraction of planets bearing life with intelligence,

$f_c$  = fraction of planets with intelligence that develops a technological phase during which there is the capability for an interest in interstellar communication,

$L$  = mean lifetime of a technological civilization.

Almost all authors agree on the general meanings of various  $f$ -parameters and  $n_e$  (though wildly differing in the values they ascribe to each of them!); on the other hand, the product  $R_*L$  is sometimes written in the form

$$R_*L = n_* \frac{L}{t_0}, \quad (2)$$

where  $n_*$  is the *current* number of stars in the Galaxy, and  $t_0$  is the age of our stellar system (currently thought to be  $t_0 \approx 12$  Gyr; e.g. Krauss and Chaboyer 2003). This is useful since (i)  $R_*$  is not a directly measurable quantity while  $n_*$  and  $t_0$  are, at least in principle, and (ii) it enables direct comparison of two characteristic timescales, cosmological ( $t_0$ ) and "astrobiological" ( $L$ ). There is a catch in (2), however, since the star formation rate is not uniform throughout the history of the Galaxy, and thus in general  $\langle R_* \rangle \neq n_*/t_0$ . While this particular problem is not acute from the SETI point of view, due to the metallicity effects (early epochs of intense star formation are characterized by low metallicity), it points in the direction of similar difficulties following from unwarranted assumptions of uniformity. We argue below that the main shortcoming of the Drake equation is its lack of temporal structure, i.e., it fails to take into account various evolutionary processes which form a pre-requisite for anything quantified by  $f$ -factors and  $n_e$ .

It is important to understand that we are criticizing the Drake equation not as an expression *per se*, but as a guiding line for a rather specific set of programs, procedures and (in the final analysis) investments, known overall as SETI. In SETI research proposals, Eq. (1) figures very prominently. Both supporters and opponents of SETI invoke the same simple numerical relationship in order to promote their respective views. However, arguments for both side are to be seriously doubted if the underlying relationship has serious deficiencies for any practical application, e.g. for estimating the timescale

for sustained SETI effort by which we might expect to detect extraterrestrial intelligent signals (or artifacts).

Probably the most telling argument as to the inadequacy of the Eq. (1) is that almost four decades of SETI projects have not given results, in spite of the prevailing "contact optimism" of 1960s and 1970s, motivated largely by uncritical acceptance of the Drake equation. Conventional estimates of that period spoke about  $10^6 - 10^9$  (!) advanced societies in the Milky Way forming the "Galactic Club" (Bracewell 1975). Nowadays, even the greatest SETI optimists have abandoned such fanciful numbers, and settled to a view that advanced extraterrestrial societies are much rarer than previously thought. One of the important factors in this downsizing of SETI expectations has certainly been demonstrations by "contact pessimists", especially Michael Hart and Frank Tipler, that the colonization—or at least visit—of all stellar systems in the Milky Way by means of self-reproducing von Neumann probes is feasible within a minuscule fraction of the Galactic age (Hart 1975; Tipler 1980). In this light, Fermi's legendary question: *Where are they?* becomes disturbingly pertinent. In addition, Carter (1983) suggested an independent and powerful anthropic argument for the uniqueness of intelligent life on Earth in the Galactic context. Today, it is generally recognized that "contact pessimists" have a strong position. How then, one is tempted to ask, does the discrepancy with our best analyses of Eq. (1) arise?

Now we shall show that there are two serious problems which make the equation (1) much less practical from the SETI point of view than has been conventionally thought. The two have the opposite effect on  $N$ , and may well partially cancel one another out; still, by a careful consideration those effects could be disentangled. Some other criticisms of the Drake equation, from different points of view, can be found in Walters et al. (1980), Wilson (1984), Ward and Brownlee (2000), and Walker and Ćirković (2003, preprint).

## 2 Upper limit on civilization's age

In principle, the parameter  $L$  in Eq. (1) could be arbitrarily large, thus offsetting any exceptionally small value among different  $f$ -parameters. Historically, that was the conventional assumption of "contact optimists" like Sagan, Shklovskii, or Drake in the earlier decades (1960s and 1970s) of SETI efforts. It is reasonable to assume that after a technological civilization overcomes its "childhood troubles" (like the threat of destruction in a nuclear war or through the misuse of nanotechnology) and starts colonizing space, it has very bright prospects for survival on timescales of millions (if not billions) years. Since it was intuitively clear (although quantified only recently; see below) that most of the inhabitable planets in the Milky Way are older than Earth, it was hypothesized that civilizations to be found through SETI projects will be significantly older than our civilization. However, it is a leap

of faith from a reasonable estimate of the temporal distribution of civilizations to the assumption that we would be able to communicate with them, or that they would express any interest in communicating with us using our primitive communication means. Even worse, people of the "contact optimism" camp have been expressing hope that we would be able to *intercept* communications between such very advanced societies, which seems still less plausible.<sup>1</sup>

Obviously, from (1) we have  $\lim_{L \rightarrow \infty} N = \infty$ , which is senseless, for the finite spatial *and* temporal region of spacetime we are considering in practical SETI. And still, remarkably, it is *not* senseless to contemplate upon the possibility that very advanced civilizations can exist indefinitely in an open universe (e.g. Dyson 1979), i.e. that the limit  $L \rightarrow \infty$  makes sense. Whether an advanced technological society can exist indefinitely—in accordance with the so-called Final Anthropic Principle of Barrow and Tipler (1986) or the Final Anthropic Hypothesis of Ćirković and Bostrom (2000)—is still an open question in the nascent astrophysical discipline of *physical eschatology* (Adams and Laughlin 1997; Ćirković 2003). Any results from it, albeit very exciting and interesting in their own right, are unimportant to SETI due to the large disparity of the timescales involved.

According to a recent study by Lineweaver (2001), Earth-like planets around other stars in the Galactic habitable zone are, on average, 1.8 ( $\pm 0.9$ ) Gyr older than our planet. His calculations are based on chemical enrichment as the basic precondition for the existence of terrestrial planets. Applying the Copernican assumption naively, we would expect that correspondingly complex lifeforms on those others to be, *on average*, 1.8 Gyr older. Intelligent societies, therefore, should also be older than ours by the same amount. In fact, the situation is even worse, since this is just the average value, and it is reasonable to assume that there will be, somewhere in the Galaxy, an inhabitable planet (say) 3 Gyr older than Earth. Since the set of intelligent societies is likely to be dominated by the small number of oldest and most advanced members (for an ingenious discussion in somewhat different context, see Olum 2003), we are likely to encounter a civilization actually more ancient than 1.8 Gyr (and probably significantly more).

It seems preposterous to even remotely contemplate any possibility of communication between us and Gyr-older supercivilizations. It is enough to remember that 1 Gyr ago, the appearance of even the simplest multicellular creatures on Earth lay in the distant future. Thus, the set of the civilizations interesting from the point of view of SETI is not open in the temporal sense, but instead forms a "communication window", which begins at the moment the required technology is developed (factor  $f_c$  in the Drake equation), and is terminated *either* through extinction of the civilization *or* through it passing

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<sup>1</sup>For a profound and poignantly ironic literary account of these issues see Lem (1984, 1987).

into the realm of "supercivilizations" unreachable by our primitive SETI means. Formally, this could be quantified by adding a term to the Drake equation corresponding to the ratio of the duration of the "communication window" and  $L$ . Let us call this ratio  $\xi$ ; we are, thus, justified in substituting  $L$  in Eq. (1) with  $\xi L$ . Since  $\xi$  is by definition smaller than unity (and perhaps much smaller, if the present human advances in communication are taken as a yardstick), the net effect would be to drastically reduce the value of  $N$ . Fortunately (from the SETI point of view) this is not the only evolutionary effect hidden in the Drake equation.

### 3 Simplicity of uniformitarianism

A still more important shortcoming of Eq. (1) as a guideline to SETI consists of its uniform treatment of the physical and chemical *history* of our Galaxy. It is tacitly assumed that the history of the Galaxy is uniform with respect to the emergence and capacities of technological societies. This is particularly clear from the form (2), as mentioned above. If, on the contrary, we assume more or less sharply bounded temporal phases of the Galactic history as far as individual terms in Eq. (1) are concerned, and take into account our own existence at this particular epoch of this history, we are likely to significantly underestimate the value of  $N$ . We shall consider such a toy model below.

Uniformitarianism has not shone as a brilliant guiding principle in astrophysics and cosmology. It is well-known, for instance, how the strictly uniformitarian (and from many points of view methodologically superior) steady-state theory of the universe of Bondi and Gold (1948) and Hoyle (1948) has, after the "great controversy" of 1950s and early 1960s, succumbed to the rival evolutionary models, now known as the standard ("Big Bang") cosmology (Kragh 1996). Balashov (1994) has especially stressed this aspect of the controversy by showing how deeply justified was the introduction of events and epochs never seen or experienced by the Big Bang cosmologists. Similar arguments are applicable in the nascent discipline of astrobiology, which might be considered to be in an analogous state today as cosmology was half a century ago.

The arguments of Lineweaver (2001) are crucial in this regard, too. Obviously, the history of the Galaxy divides into at least two periods (or phases): before and after sufficient metallicity for the formation of Earth-like planets has been built up by global chemical evolution. But this reflects only the most fundamental division. It is entirely plausible that the history of the Galaxy is divided still finer into several distinct periods with radically different conditions for life. In that case, only *weighted relative durations* are relevant, not the overall age.

Exactly such a picture is presented by a class of phase transition models (Clarke 1981; Annis 1999; see also Norris 2000), which assume a *global reg-*

*ulation mechanism* for preventing the formation of complex life forms and technological societies early in the history of the Galaxy. Such a global mechanism could have the physical form of  $\gamma$ -ray bursts, if it can be shown that they exhibit sufficient lethality to cause mass biological extinctions over a large part of the volume of the Galactic habitable zone (Scalo and Wheeler 2002). If, as maintained in these models, *continuous habitability* is just a myth, the validity of the Drake equation (and the spirit in which it was constructed and used) is seriously undermined.

For illustration, let us assume that the parameter  $f_l$  has the following evolutionary behavior:

$$f_l = \begin{cases} 10^{-6} & : 0 < t \leq t_p \\ 0.9 & : t_p < t \leq t_0 \end{cases} . \quad (3)$$

(we put the zero of time at the epoch of the Milky Way formation). Here,  $t_p$  is the epoch of global "phase transition" (Annis 1999), i.e. the epoch in which the lethal Galactic processes became rare enough for sufficiently complex lifeforms to emerge. Let us take  $t_0 = 12$  Gyr and  $t_p = 11$  Gyr. Naive uniformitarian application of the Drake equation would require us to find the average  $\langle f_l \rangle$  in particular example  $\langle f_l \rangle = 0.072$ ; if we assume  $n_e = 1$ , other  $f$ -factors all equal to 0.1 (rather conservative assumption), and  $R_* = 5 \text{ yr}^{-1}$ , we obtain that  $N = 3.6 \times 10^{-5} \xi L$ , where  $L$  is measured in years, and  $\xi$  is the relative duration of the communication window discussed above. In fact, the true result is rather  $N = 4.5 \times 10^{-4} \xi L$ , more than an order of magnitude higher. Such a big difference is of obvious relevance to SETI; if  $\xi L \sim 10^5$  yrs or less, it might as well be the difference between sense and nonsense in the entire endeavor. The discrepancy increases if the epoch of the phase transition moves closer to the present time. The latter is desirable if one wishes to efficiently resolve Fermi's "paradox" through phase-transition models.

More realistically, we would expect several of the  $f$ -factors, as well as  $n_e$ , to exhibit secular increase during the course of Galactic history in a more complicated manner to be elaborated by future detailed astrobiological models. Yet, steps similar to the one in (3) seem inescapable at some point if we wish to retain the essence of the phase transition idea. Barring this, the only fully consistent and meaningful idea for both explanation of the "Great Silence" and retaining the Copernican assumption on Earth's non-special position is the "Interdict Hypothesis" of Fogg (1987), as the generalized "Zoo Hypothesis" (Ball 1973), which still seems inferior, since it explicitly invokes non-physical (e.g., sociological) elements.

Intuitively, it is clear that in such phase transition models it is a very sensible policy for humanity to engage in serious SETI efforts: we expect practically all ETI societies to be roughly of the same age as ours, and to be our competitors for Hart-Tiplerian colonization of the Milky Way. The

price to be paid for bringing the arguments of "optimists" and "pessimists" into accord is, obviously, the assumption that we are living in a rather special epoch in Galactic history—i.e. the epoch of "phase transition". That such an assumption is entirely justifiable in the astrobiological context will be argued in a subsequent study. (Parenthetically, this is entirely in accord with the tenets of the currently much-discussed "rare Earth" hypothesis; see Ward and Brownlee 2000.)

Note that in this case, the overall average age of a civilization ( $L$ ) would give an entirely false picture at the outcome of the Drake equation. In the toy model above, any hypothetical civilization age of (say) 10 Gyr is obviously irrelevant (although possibly sociologically allowed). This conclusion is valid even if the width of the communication window is very large, and in fact spans most of the lifetime of a civilization, as SETI pioneers claimed ( $\xi \approx 1$ ). Thus, we obtain a physically more desirable picture for the explanation of Fermi's "paradox" in which sociological influences are much less relevant.

## 4 Conclusions

We conclude that the Drake equation, as conventionally presented, is not the best guide for both operational SETI and future policy-making in this field. The reason for this is its lack of temporal structure and appreciation of the importance of evolutionary effects, so pertinent in the modern astrobiological discourse. If we wish to go beyond the "zeroth-order" approximation encapsulated by (1), we will need to account for evolutionary effects, such as metallicity build-up and "catastrophic" regulation of habitability. Notably, the non-uniform history of the Galaxy as conceived in the phase transition models can accommodate both the arguments of "contact pessimists" and the justification for SETI projects, which have been deemed incompatible in the literature so far. Future detailed modeling will show in which way we can best accommodate our knowledge on the history of the Galaxy in the overall astrobiological picture.

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