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Research Paper

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 research on extraterrestrial intelligence. It is shown that the Drake equation tacitly relies on unverified assumptions on both the physicochemical history of our galaxy and the properties of advanced intelligent communities. In this manner, the conventional approach fails to take into account various evolutionary processes forming prerequisites for quantification of the Drake equation parameters. The importance of recent results of Lineweaver and collaborators on chemical build-up of inhabitable planets for the search for extraterrestrial intelligence is emphasized. Two important evolutionary effects are briefly discussed, and the resolution of the difficulties within the context of the phase-transition astrobiological models is sketched. Key Words: Galaxy:evolution—Extraterrestrial intelligence—History and philosophy of astronomy. Astrobiology 4, 225–231.

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 the 21st 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 (Drake, 1965).

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 investigate the following form (see, *e.g.*, Shklovskii and Sagan, 1966; Walters *et al.*, 1980; Duric and Field, 2004):

$$N = R_* f_g f_p n_e f_l f_i f_c L \qquad (1)$$

while keeping in mind that other equivalent forms exist. 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

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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; and L = mean lifetime of a technological civilization. Almost all authors agree on the general meanings of various f parameters and n_e (though the values ascribed to each differ by several orders of magnitude!); on the other hand, the product R_*L is sometimes written in the form

$$R_* L = n_* \frac{L}{t_0} \tag{2}$$

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 $t_0 \sim 12$ Gyr (see, *e.g.*, Krauss and Chaboyer, 2003)]. This is useful since (i) R_* is not a directly measurable quantity [The problem of evolution of the star-formation rate in spiral galaxies has been recently been tackled from both local (nearby galaxies) and the large-scale galaxy survey perspectives. These studies shed some light on the mean star-formation rate during the entire history of a spiral galaxy (see Hopkins *et al*., 2001; Panter *et al*., 2003; Hartwick, 2004).], while n_* and t_0 are, at least in principle, and (ii) it enables direct comparison of two characteristic time scales, cosmological (t_0) and "astrosociological" (L). There is a catch in Eq. 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, because of the metallicity effects (early epochs of intense star formation are characterized by low metallicity, preventing formation of habitable planets), 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 that form a prerequisite for anything quantified by f parameters and n_e.

It is important to understand that we are criticizing the Drake equation not as an expression *per se*, but as a guideline 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 sides are suspect if the underlying relationship has serious deficiencies for any practical application, *e.g.*, for estimating the time scale for sustained SETI effort by which we might expect to detect extraterrestrial intelligent signals (or artifacts).

In 4 decades of SETI projects there have been no 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). Today, even SETI optimists have abandoned such fanciful numbers, and settled on a view that advanced extraterrestrial societies are much rarer than previously thought. One of the important factors in this downsizing of SETI expectations has been demonstration 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; Jones, 1976; Tipler, 1980, 1981). In this light, Fermi's legendary question, "*Where are they?*," becomes disturbingly pertinent (Webb, 2002). In addition, Carter (1983) suggested an independent and powerful anthropic argument for the uniqueness of intelligent life on Earth in the galactic context. 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?

We show that there are two difficulties that make Eq. 1 much less practical from the SETI point of view than 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 decoupled. Some other criticisms of the Drake equation, from different points of view, can be found in Walters *et al*. (1980), Tipler (1980), Wilson (1984), Mash (1993), Ward and Brownlee (2000), and M.A. Walker and M.M. Ćirković (unpublished data). Some of these accounts mention in passing the difficulties arising from changing of one or more parameters in Eq. 1 with time, *e.g.*, Mash (1993) relegates this problem to a footnote, but a more elaborate treatment of these evolutionary aspects is still lacking. Proponents of vigorous SETI research, including Frank Drake himself, have also from time to time mentioned the lack of temporal structure as one of the disadvantages of this equation (see, *e.g.*, Drake and Sobel, 1991), but avoided the discussion of systematic biases following such simplification.

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 time scales of millions or even billions of 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. [For a profound and poignantly ironic literary account of these issues see Lem (1984, 1987).]

Obviously, from Eq. 1 we have $\lim_{L\to\infty} N = \infty$, 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 (see, *e.g.*, Dyson, 1979), *i.e.*, that the limit $L \to \infty$ 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 because of the large disparity of the time scales 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 ± 0.9 Gyr older than our planet (see also the extension of this study by Lineweaver *et al*., 2004). 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 life forms on those others to be *on the 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 a small number of oldest and most advanced members (for an ingenious discussion in somewhat different context, see Olum, 2004), we are likely to encounter a civilization actually more ancient than 1.8 Gyr (and probably significantly more).

It seems preposterous even to contemplate any possibility of communication between us and Gyr-older supercivilizations. Remember that 1 Gyr ago the appearance of even the simplest animals on Earth lay in the distant future. [Ediacaran fauna—a kind of fuse on the the famous Cambrian Explosion—is now being dated at "only" 565–543 Myr before the present (see, *e.g.*, Conway Morris, 1990).] 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 its passing 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 ξ; we are, thus, justified in substituting L in Eq. 1 with ξL. Since ξ 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 bias hidden in the Drake equation.

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 of Eq. 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 consider such a 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—by the Big Bang cosmologists—of events and epochs never seen or experienced. 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 regulation 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 γ-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; see also Thorsett, 1995; Melott *et al.*, 2004). 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:

$$f_l = \begin{cases} 10^{-6}, & 0 < t \leq t_p \\ 0.9, & t_p < t \leq t_0 \end{cases} \tag{3}$$

(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 life forms 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, as an example $\langle f_l = 0.072 \rangle$; if we assume $n_e = 1$, other f parameters all equal to 0.1 (a rather conservative assumption), and $R_* = 5$ years^{-1}, we obtain $N = 3.6 \times 10^{-5} \xi L$, where L is measured in years, and ξ is the relative duration of the communication window discussed above. In fact, the true result is instead $N = 4.5 \times 10^{-4} \xi L$, more than an order of magnitude higher. Such a big difference is of obvious relevance to SETI; if ξL is $\sim 10^5$ years 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.

In particular, Annis (1999) argues that the rate of γ-ray bursts in an average galaxy declines as $\propto \exp(-t/\tau)$, where τ is ~ 5 Gyr. Only a very slight improvement in the "step" model above would be to filter the same parameter f_l in accordance with this rate, by assuming that the (ensemble-averaged) probability of evolving complex life forms is inversely proportional to the γ-ray burst rate during the history of the Milky Way. A model with $f_l(t) = f_*(e^{t/\tau} - 1)$, where with f_* we denote everything dependent on astrobiological parameters other than time, normalized to the present-day $f_l(t_0) = 0.9$ gives the time-average of $\langle f_l \rangle = 0.28$. The discrepancy is thus about half an order of magnitude. No specific conclusions should be drawn from toy models such as these, except the general conclusion that in phase-transition models the relationship between time and abundance of life is more complicated than usually assumed. On the balance, this approach favors SETI more than the Drake equation. Deeper understanding of the specific effects of forcing influences (for instance, the atmospheric chemistry in the aftermath of a galactic γ-ray burst or the controversial issue of the cosmic-ray generation in γ-ray bursts) will bring us to the more satisfactory quantitative relationship between the galactic astrophysical evolution and the specific terms in the Drake equation, notably f_l and f_i.

More realistically, we would expect several of the f parameters, 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 Eq. 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.

A recent important study by Lineweaver *et al.* (2004) analyzes the astrobiological evolution of the Galaxy in time versus parameters such as metallicity and frequency of life-extinguishing supernovae. The results confirm previous ones by Lineweaver (2001), but add several new features. The galactic habitable zone is an annular ring of the Milky Way thin disk that widens with time, consisting of stars formed between 8 and 4 Gyr ago. From the SETI point of view, this makes Fermi's paradox more serious, since 75% of the stars in the galactic habitable zone are older than the Solar System. However, in seeming contrast to the phase-transition models discussed here, the solution of Lineweaver *et al.* (2004) indicates a rather gradual transition between the uninhabitable and inhabitable part of the galactic history. This transition results from the metallicity buildup coupled with the decrease in frequency of supernovae with time. This is not incompatible with the phase-transition models, in the same sense as continuous existence of life on Earth is not incompatible with the mass extinctions of biota occuring from time to time. The main argument for compatibility is that here we are concerned primarily with the problem of the distribution of *intelligent* life—the subject matter of SETI—which clearly requires much sharper filtering of points in space and time, being much less robust in response to adverse environmental changes (including supernovae and γ-ray bursts) than life in general. An additional important difference is that smoothing the spatiotemporal distribution of supernovae applied by Lineweaver *et al.* (2004) is probably not applicable to much rarer and much more destructive γ-ray bursts, which according to Scalo and Wheeler (2002) can seriously impair biospheres in the entire galactic habitable zone.

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 extraterrestrial intelligent societies to be roughly of the same age as ours, and to be our competitors for Hart-Tiplerian colonization of the Milky Way. This class of models underlines the essential weakness in the "contact pessimist" position; as Tipler (1980) wrote: "[pessimist] argument assumes that the . . . probabilities of the Drake equation do not vary rapidly with galactic age." Phase transition is exactly such a "rapid variation." 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 (by an observation–selection effect) 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 (Ward and Brownlee, 2000).

Note that in this case, the overall average age of a civilization (L) would give an entirely false picture of 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). Thus, the universally disliked sensitivity of N on L and all its "astrosociological" baggage is diminished, at least in the limit of large values of L. This conclusion is valid even if the width of the communication window is very large or spans most of the lifetime of a civilization, as SETI pioneers claimed ($\xi \sim 1$). In these cases, the relevant time scale is not something inherent in the biosphere/noosphere, but the external forcing time scale, *e.g.*, the time elapsed since the last catastrophe. Thus, we obtain a physically more desirable theoretical framework for the explanation of Fermi's paradox in which sociological influences are much less relevant.

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 Eq. 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 incorporate our knowledge of the history of the Galaxy in the overall astrobiological picture.

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ABBREVIATION

SETI, Search for ExtraTerrestial Intelligence.

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