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A Redefinition of the Drake Equation and Its Implications for Astrobiology

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Abstract

The search for life on other planets in our own solar system, the other star systems in the Milky Way, and other galaxies in the observable universe is a newly-growing field. Searching for planets that may be habitable to life is essentially a series of probabilistic observations, facilitated by the summation of multiple variables that affect the development of life. Through the past 100 years, what science defines as the requirements of living organisms has been broadened, causing a widening of the search window for extraterrestrial life. Since the publication of Frank Drake's famous equation, the search for life on other planets has become a topic of great interest in the fields of biology, chemistry, and astronomy. This paper investigates Drake's initial equation and considers possibilities for its alteration. Primarily, the original formula applies only to intelligent extraterrestrial life, but with changes it can be applied to the search for life of any sort. By considering what biology regards to be requirements of all known life (such as carbon, liquid water, etc.), the same restrictions can be applied to the search of the cosmos. To begin changing the equation, we must consider the requirements for life and ways to incorporate them into the formula in the form of unique variables, each pertaining to a restriction of life. Upon completion, it will be possible to take any body (planet or planetary moon), consider its characteristics, and incorporate them into the equation, and the formula will provide the probability for the presence of life on the body. The resulting likelihood of habitability is relevant to both the general habitability of the body and the existence of life itself. With the final equation, astrobiologists will be able to quickly determine which star systems are more likely to support life; giving the field a method to expedite the extraterrestrial search.

Keywords: Astrobiology, Exobiology, Drake Equation

1. Introduction

1.1 The Drake Equation

In 1961, radioastronomer Frank Drake formulated a probabilistic equation designed to estimate the likelihood of communicative extraterrestrial civilizations on a certain planet whose characteristics were known. The equation was designed to be less of a serious outlet of application for astrobiology and more of a way to get the scientific community to begin considering the search for life on other planets. At its birth, many of the variables described in Drake's equation were entirely unknown.

Drake's original formula related the number of communicative extraterrestrial civilizations (N) to the product of six variables.

$$N = R_* \cdot f_p \cdot n_e \cdot f_l \cdot f_i \cdot f_c \cdot L \quad (1)$$

R_* is the average rate of star formations in the Milky Way galaxy; f_p is the fraction of formed stars which already have planets of any sort in orbit around them; n_e is the average number of planets in each star system that can potentially support life; f_l is the fraction of those planets defined in the variable n_e on which life does develop; f_i is the fraction of planets on which life develops that go on to develop intelligent life; f_c is the fraction of planets on which intelligent life develops, said intelligent life goes on to become communicative; L is the length of time over which such intelligent, communicative civilizations, as defined in the variable f_c, release detectable signals[1]. Each of these variables have been assumed to be a number between zero and one which, when evaluated, would result in a percent value.

Equation (1), while groundbreaking for the sciences at the time, is flawed in its number, type, definition, and arrangement of the variables. The equation in its original form merely specifies the likelihood of advanced civilizations existing[2]. However, the equation can be modified to account for all life if the variables used are catered to reflect the current understanding of life's requirements and the variables which pertain to intelligent life are discarded. The equation can thus be expanded to be used in a general search of life of all types, not simply advanced, intelligent (presumably multicellular) life. For the extent of this paper, the variables associated with the novel equation that are presented are also intended to be values between zero and one, which will, similar to Drake's equation, ultimately yield a percentage for the final value of the new formula.

Currently, the knowledge of biology applies only to the life to which science has been exposed, that is, life on Earth. Thus, the ability to predict the characteristics of non-Earth life is limited. Indeed, Earth's holding of life has been found to be quite unique in the observable universe[3] (this observation also leads to the realization that it is not likely for life to begin, for if it was, life would be much more common than is currently known and thus seen on other bodies instead of exclusively on earth). Additionally, it has been stated that science does not yet have the capabilities to wholly and completely accurately, without any ambiguity, define what is and is not alive[4]. This ambiguity, along with questions about life's requirements will prove to be important in discussions to come regarding non-earth life.

To begin, it is inarguable that all life (whether on Earth or elsewhere) is likely to possess some properties that are associated with known biological processes and living organisms on Earth[5] which are used to qualitatively separate the biotic from the abiotic. Indeed, if there were no similarities between all life in the universe, it would be almost impossible to discover life existing elsewhere. It is important to note that if life has developed on non-Earth bodies, the origin events between the various oases of life in the cosmos would likely be entirely unrelated events. This leads to questions regarding origins of life on Earth and how life gets started. These questions are unfortunately beyond the scope of this paper.

A few distinct and required characteristics that an organism must possess to be considered alive have been defined by biology. That is, a thing is living if it is made of cells, has a metabolism, can reproduce and pass on its genetic information, can maintain a stable internal environment (homeostasis), can grow and develop, can respond to stimuli, contains a genetic code, and can adapt and its progeny can be subject to Darwinian evolution. The qualities and requirements of life on another planet can be carefully imagined, based mainly on observations of the requirements of life on Earth such as liquid water, the elements carbon, nitrogen, oxygen, and hydrogen, or a primary source of energy (i.e. the Sun or chemical compounds). However, it is extremely difficult to imagine a novel organism which is missing one of these many qualities without descending into science fiction.

1.2 Bare Necessities

To begin to redefine the Drake equation, a list of requirements must be made for life, from its origins to its proliferation, beginning solely with its home. Life is more likely to be observed on a stable body in a formed solar system because it is less likely to be eradicated before biological processes can truly begin if there is as little chaos as possible. Additionally, the type of life considered in the redefined equation should be specified. Drake only considered the search for intelligent life[6]; this new equation will consider the presence of any life, including single-celled organisms. Before variables can be redefined and new ones considered, the final three variables pertaining to intelligent life in Drake's original equation must be discarded, along with the variable f_l because it defines the development of life (which is inconclusive and nonspecific), in order to build a new function. Thus, one could construct a new equation

$$N = R_* \cdot f_p \cdot n_e \quad (2)$$

which can serve as a template for the reevaluation of the Drake equation.

First, a source of energy is needed to drive life's existence. This origin of energy is most familiarly known as a host star (R_S), but may also exist as chemical sources within the body. Next, a planet or planetary moon on which life can develop (S_P) is needed, for without stable ground, cells would be forced to assemble without a substrate and in the vacuum of space. Finally, specific requirements for the formation of life are needed to begin assembly of the first cells. Specific requirements include pH and temperature limits[7], the presence of chemicals utilized in biological systems (P_C), and the presence of a protective atmosphere on the body in question (p_A). Taking these into consideration, and building upon equation (2), a foundation to the new equation is born.

$$N = R_S \cdot S_p \cdot P_C \cdot p_A \tag{3}$$

Equation (3) will serve as the basis for the incorporation of new variables and the discovering of life on other bodies, though a slight rearrangement is required.

$$\mathbb{P} = \Omega \cdot \Phi \tag{4}$$

Once completed, the final equation will consist of two terms: one consisting of all solar factors relating to the development and support of life (Ω), including R_S and S_p, and the other consisting of all planetary factors relevant to life (Φ), including P_C and p_A. The product of these will give $\mathbb{P}$. Thus, equation (3) can be rearranged to yield equation (4). Due to the probabilistic nature of these equations, this paper follows Drake's example with variables and again assumes each is equal to a number less than one. Thus, each variable x within Ω and Φ will exist such that $0 \leq x \leq 1$. Therefore, both Ω and Φ will exist such that $0 \leq \Omega \leq 1$ and $0 \leq \Phi \leq 1$. Equation (4) demonstrates the final form of the finished equation, and will exist such that $0 \leq \mathbb{P} \leq 1$. If a body does not meet a necessary requirement of life, then the value for that variable will be zero. This will make the value of the entire term also zero, and thus, $\mathbb{P}$ would equal zero. This is reasonable because if a planet does not contain a needed component for life's existence, the probability of life developing on that body would be essentially zero.

After this revision step, the equation is potentially applicable to any living organism that may have developed in the universe, though it is still far from complete. From here, new variables can be defined and more requirements of life can be considered. It is now necessary to begin describing variables comprising Ω and Φ to develop the new equation into a more comprehensive formula that can be easily applied to the search for extraterrestrial life.

2. Biological Requirements

While it has been noted that the search for extraterrestrial life could yield the discovery of advanced civilizations[8,9,10], the likelihood of the development of complex (multicellular) organisms is lower than that of single-celled organisms. This is evidenced by the earth's own natural history: from the origin of life at approximately 3.5 billion years ago[11,12,13,14,15,16] to the introduction of early multicellular organisms at approximately 575 million years ago[17], there spans a vast time in which the earth was inhabited exclusively by unicellular organisms. Indeed, single-celled organisms have existed for the entire history of life on earth, including the present, while complex life (such as plants, fungi, and animals) are still relatively new. Thus, it is reasonable that if life exists elsewhere in the universe, there are more planets harboring unicellular organisms than there are with complex life. It is therefore important to consider the most basic requirements for a cell when choosing new variables for the revised equation to create a formula that is applicable to all life.

For a planet to develop and support life, there is a need to satisfy all requirements of living things. If not all needs are met, life cannot survive. Thus, a critical need is produced, where a critical need is a requirement of biological systems to support their processes. Critical needs will play a role in each variable described in the new equation and, if met, will provide a greater likelihood for the development of life.

2.1 Solar Factors (Ω)

"Solar factors" is a blanket term to cover any characteristics of a planet's location and conditions in space that may affect the development and survivability of life. This can range from the planet's galactic location to the presence of any moons in orbit around the planet, all of which can potentially have an impact on the development of life. Indeed, it is out of this chaos that opportunities for life arise[18].

$$\Omega = S_L \cdot S_R \cdot S_A \cdot S_T \cdot S_S \quad (5)$$

Many characteristics of a planet's galactic neighborhood, given in equation (5), are important for the potential development of life. Beginning with the location within its galaxy (S_L), certain areas therein are less turbulent and more forgiving than others[19], thus presenting a better opportunity for life to develop[20]. The type of star the planet orbits and the subsequent radiation experienced on the planet's surface (S_R) is also important. This is partially dependent on the planet's atmosphere[21] (S_A), which determines the temperature range on the planet's surface[22] (S_T), and thus the area in which water can exist as a liquid and by extension where life is most likely to succeed, called the habitable zone[23] (Figure 1). Each of these factors, along with any additional requirements (S_S), represent a portion of the planet's astronomical neighborhood, the culmination of which must be agreeable enough to allow the development of life.

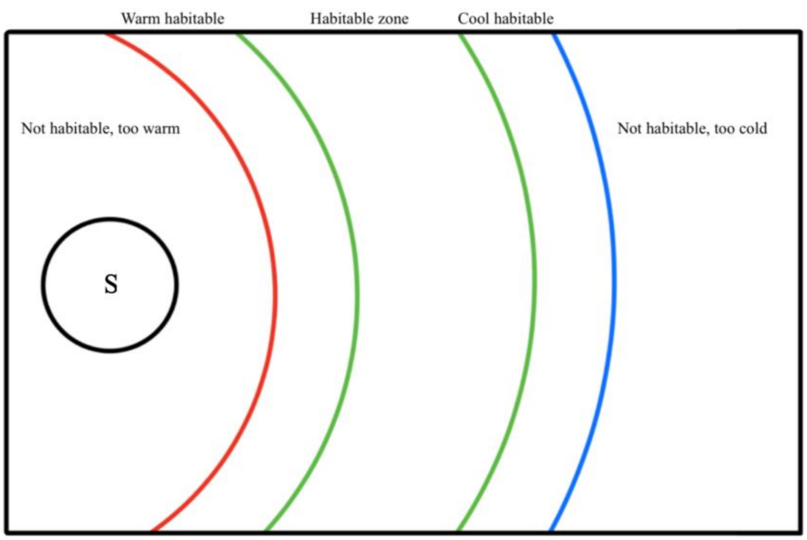

Figure 1. An illustration of the habitable zone around a hypothetical star, S. The habitable zone is generally defined as the region around a star where life is most likely to exist.

Some habitable zones can be extended due to different combinations of characteristics of the solar system. Habitable zones should include a zone most likely to hold liquid water, and a slight extension in either direction to account for these variables (i.e. "warm habitable" and "cool habitable"). These variations in the habitable zone are mainly due to differences in solar radiation per unit area given by the star, a planet's atmospheric density, and other factors which may impact the amount of energy available on the planet's surface. These relations are somewhat given by the following expression, which relates Angot radiation (extra-terrestrial solar radiation) as a function of a planet's distance from its host star[24]. Equation (6) below uses earth as an example, but could be applied to any planet in question.

$$R_A = \frac{(86400)(1360)}{\pi}\left(\frac{d_m}{d}\right)^2 \times [(H_s)\sin(\alpha)\sin(\delta) + \cos(\alpha)\cos(\delta)\sin(H_s)] \quad (6)$$

where R_A is Angot radiation (in $MJm^{-2}day^{-1}$), d is the distance between the sun and the earth (in km), d_m is the mean distance from the sun to the earth (in km), α is the latitude on the earth (in rad), δ is the solar declination (in rad), and H_s is the solar angle at sunrise (in rad). Using this equation, it is possible to calculate solar radiation at any point in the earth's outer atmosphere.

2.2 Planetary Factors (Φ)

The planetary factors encompass any characteristics of a planet that pertain to the development and support of life thereon. The character Φ represents anything from the elemental composition of the planet to the energy available for use by potential life forms.

With the fundamental building block of all life, carbon (C)[25,26], life was able to begin on Earth and along with other elements and chemicals, such as water (W), nitrogen (N), hydrogen (H), methane (M), and ammonia (A), it is presumable that the abiogenic synthesis of biological compounds could lead to the origins of life[26] on other planets. Thus, the variable P_C represents the summation of these essential substances, along with an additional variable (*f*) to represent any trace substances that are also essential for life.

In addition to the elemental bases, biological life requires some form of energy, either from the sun (via photosynthesis) or from chemical energy within the environment[27]. The variable P_E will represent the energy available to photoautotrophs (E_{Photo}) or chemoautotrophs (E_{Chemo}) on the planet. These autotrophs will likely form the foundations for any ecosystems found on a foreign planet, just as they do on earth.

$$P_C = C + W + N + H + M + A + f \tag{7}$$

$$P_E = E_{Photo} + E_{Chemo} \tag{8}$$

With the combination of equations (7) and (8), and an additional variable (P_P) to show any other not yet described factors relevant to the planetary term, Φ begins to take shape, leading to its following revision.

$$\Phi = P_C \cdot P_E \cdot P_P \tag{9}$$

2.3 The Final Equation (ℙ)

Via equations (4), (5), and (9), along with an additional variable (N_N) to represent factors not yet described here, the structure for the new formula is complete.

$$\mathbb{P} = \Omega \cdot \Phi \cdot N_N = (S_L \cdot S_R \cdot S_A \cdot S_T \cdot S_S) \cdot (P_C \cdot P_E \cdot P_P) \cdot N_N \tag{10}$$

where $0 \leq \mathbb{P} \leq 1$.

It has been demonstrated that a system containing all necessary pieces of biological macromolecules, along with a form of energy, can produce amino acids[28]. It is therefore plausible that a planet with all necessary requirements given enough time would theoretically be capable of producing life. Should all aspects of the equation be satisfied by a value of each variable being in a sufficiently small neighborhood of the critical need, then the value of $\mathbb{P}$ would reflect a promising likelihood of the planet in question developing life.

3. Earth as a Test Case

To provide an example of the usefulness of equation (10), estimated values for earth have been substituted into the equation below. Earth is used as an example here because it is known to be inhabited by life, and therefore its value of $\mathbb{P}$ must be greater than zero, but not so great to imply an easy start for life. Please note that some of these values here have been skewed because of the knowledge of some of Earth's characteristics and many are estimated to the author's greatest abilities (i.e. due to the knowledge that Earth's host star supports life and that Earth lies within its star's habitable zone, the value of Ω has been set to one).

If the value of P_C is equated to approximately 0.90, due to the relatively large abundance of carbon, nitrogen, oxygen, and other trace elements available on the earth's surface, the value of P_E is set to one, as energy is captured by life both from the sun (see Angot radiation discussed above[24]) and from other sources (i.e. hydrothermal vents[27]), and the value of P_P is estimated to be approximately 0.5 (because on the earth's surface, the requirements for life are of course present, but their relative abundance is unsure or uneven), then a reasonable estimate for the equation considering earth is made. Thus, the value of $\mathbb{P}$ is estimated to be approximately 0.45.

This value represents what may be described as an expected result. Life on earth obviously exists; its genesis is not only shrouded in mystery, but also assumed to be quite unlikely. Thus, a less-than likely probability is deemed reasonable for the origin-of-life scenario currently being investigated. Of course, a deeper understanding of life's origins would provide more insight into some of these values, but $\mathbb{P} = 0.45$ is a reasonable first-conclusion for the applications of this equation.

4. Discussion and Conclusion

The proposed augmentations to the Drake equation described in this paper will eventually culminate in a final, finished equation. Upon full completion of equation (10), it will be possible to consider any body (planet or planetary moon), consider its characteristics and values in the proposed equation, and receive a value for the percent likelihood of the habitability of the body in question. The value that will be calculated for $\mathbb{P}$ speaks to both the potential habitability of the body as well as the ability for life to have self-generated on that body. Once $\mathbb{P}$ is calculated, it will be possible to apply this work alongside missions already focused on finding life elsewhere in the universe. However, it will be unfortunately impossible to confirm the predictions made by this equation without sampling of the body itself, which for some planets and moons in question is not yet a feasible task. As it stands, the equation is incomplete because of a lack of data for extra-solar planets, this is will be remedied by additional exploration and data gathering, which will allow for each value of the equation to be known.

The original Drake equation was meant to serve as a thought experiment. This revision has taken the equation from a mere thought experiment. to a state of applicability. Now with new terms defines, the revised equation can determine which extra-solar planet(s) in question are more likely to hold life, making mankind's search more efficient and more targeted. This revision to the Drake equation is meant to serve as a tool for continuing the search for life elsewhere in the universe. The final product presented in this paper, equation (10), is in no way complete, hence the continuation of each individual term with a variable that acts as a placeholder for additional factors to be incorporated (see equations (5-9)). Further work in this area will include the further construction of each component of the equation to incorporate more variables in an effort to make the final equation more accurate. Additionally, new ideas and research involving the origin of life and astrobiology will shed increasingly more light on the applicability of this project.

As more discoveries are made in the biological sciences and as the extreme ranges in which life can survive are broadened, the search for life on other planets will also be expanded. For example, based on the discovery of ecosystems founded on energy from hydrothermal vents, it is possible that life could survive purely on chemical output from hydrothermal vents or other equivalent circumstances on other planets. Additionally, the growing interest in the biology of the lithosphere suggests that life might also be able to exist in the rocks of an otherwise barren planet. In short, it is important to remember that life is flexible, it is opportunistic, and it is very often robust. The search for life on other planets ought not be limited to the patterns seen on Earth, but should instead use Earth as a guide for the search elsewhere, as extra-solar life may look nothing like life on earth.

Given the size of the universe and the knowledge that self-originating life (like that found on Earth) is possible, it is plausible that in the vastness of the universe life exists elsewhere; it simply needs to be found. That can hopefully be accomplished in part using the finished product of the equation put forth in this paper.

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