Petar Nurkić
Institute for Philosophy
Faculty of Philosophy University of Belgrade
E-mail: petar.nurkic@f.bg.ac.rs

Original Scientific Paper
UDC: 575.8:167/168
113:167/168
573.5:1

DARWIN MEETS DR. FRANKENSTEIN: USING THE DRAKE EQUATION TO CALCULATE THE PROBABILITY OF VOLCANIC LIGHTNING'S IMPACT ON CHEMICAL EVOLUTION

Abstract: *Horizontal gene transfer (HGT) has been a paramount mechanism of interest in recent literature addressing the origins of biological evolution. However, research on lightning-triggered electroporation represents the innovative and still insufficiently grasped approach to HGT (Kotnik, 2013). On the other hand, prebiotic synthesis is a fundamental process for chemical evolution. Recently, the effects of volcanic lightning on nitrogen fixation and phosphate reduction have also been considered (Navarro-González and Segura, 2004). This paper aims to present a top-down approach to the question of the origin of life on early Earth. By considering the conditions necessary for the emergence of biological and chemical evolution, emphasizing electrostatic discharges, we will attempt to link previous theoretical and experimental research. Furthermore, we will present a recent endeavor at applying the Drake equation to calculating the probability of volcanic lightning impact on the prebiotic synthesis and derive a similar use in estimating the contribution of lightning to HGT (Weaver, 2013). We will also display that choosing a type of probability appropriate for the context of life sciences is not necessarily a quantitative issue. Finally, we will show that significant conceptual constraints, like determining the relevant factors and sources of uncertainty when considering the origin of life on early Earth, are fundamentally philosophical issues. We hope that the results of our research – deriving Drake's equation in the domain of chemical evolution and considering Bayesian and counterfactual types as potentially more suitable candidates for calculating probabilities in the evolutionary framework – will contribute to developing new discussions in life sciences.*

Keywords: *biological evolution, chemical evolution, horizontal gene transfer, prebiotic synthesis, volcanic lightning, Drake equation.*

1. Introduction

A wide variety of scientists interested in questions about the origin of life believe that the first living cells were created by a natural process called chemical evolution. However, when we talk about evolution, we focus mainly on its biological aspects: reproduction, variation, and selection (Sober, 2006: 11–16). To examine chemical evolution and how it differs from biological evolution, we need to define key concepts in chemistry and biology and demonstrate how chemical evolution creates complex systems from simple molecules that form a similar structure that we can find in living cells[1].

Evolution, simply put, is change over time. This change is focused primarily on biological organisms that can reproduce. Change over time in biological evolution places great emphasis on survival. If an individual can survive, it also gets the opportunity to reproduce and make „copies of itself" while entire populations develop new traits and abilities. Reproduction, variation, and selection as the basis of biological evolution can be illustrated by focusing on Plant X and Y (Obeso, 1997). Suppose Plant X has leaves with smooth edges, while Plant Y, which belongs to the same species, has spines that allow it to vary. The natural habitat of Plants X and Y are deciduous forests where herbivores are abundant. Plant Y is harder to eat because the thorns are not particularly pleasant for chewing and digestion and therefore have a higher probability of survival and reproduction. Nature sometimes quite arbitrarily places barriers to survival and selects opportunities for reproduction and the transmission of traits to new generations. In the case of Plants X and Y, the spiny leaf mutation represents a new trait that provides a distinct survival advantage.

The problem underlying biological evolution is the necessity of reproduction to function properly[2]. Complex reproduction process gives rise to the question: how did evolution initially evolve? To answer this meta-question, researchers turn to chemical evolution (Ruiz-Mirazo et al., 2017). In chemical evolution, we can observe changes in organisms that cannot reproduce. These changes are relatively simple, such as iron corrosion when it comes into contact with water. Nevertheless, no matter how minimal their effect, simple chemical changes lead to the formation of organisms capable of reproducing and acquiring new traits. Thus, the main difference between biological and chemical evolution is that reproduction is replaced by a more straightforward process – repetitive production (Rauchfuss, 2008: 21–29).

As we have indicated, this paper aims to take a top-down approach to questions about the origin of life on the early Earth, with particular emphasis on electrostatic discharges, or lightning, as triggers of natural processes

1 Our paper does not aim to show the influence of lightning on the occurrence of chemical or biological evolution but evolution in general. Although it can be more challenging to follow, we will provide key aspects of chemical and biological evolution in parallel. The rationale for this approach is the continuous retention of the general characteristics of evolution as an umbrella phenomenon. With this parallelism, we will single out the similarities of the origin of life on different explanatory levels and more easily illustrate the key philosophical problems of calculating probability in evolutionary domains.

2 For recent research considering the possibility of biological evolution with natural selection but without reproduction, see Papale (2021). To achieve the goals of our paper, we will consider the more traditional assumption of reproduction as a necessary condition for evolution.

responsible for the emergence of evolution. Therefore, the second chapter focuses on biological evolution, in which we describe horizontal gene transfer and electroporation as central phenomena responsible for the exchange of intercellular material between unicellular organisms. In the third chapter, we describe the process of prebiotic synthesis and the elements necessary for chemical evolution – nitrogen and phosphorus. For nitrogen and phosphorus to participate in prebiotic synthesis, they must be converted to ammonia and hydrophosphates through processes of nitrogen fixation and phosphate reduction. The stimulating environment of volcanic gas and ash clouds that generate volcanic lightning is the necessary condition for these conversion processes. In the fourth chapter, we present an attempt to apply the Drake equation to calculate the probability of the influence of volcanic lightning on the origins of chemical evolution. Finally, we will attempt to apply the same equation to calculate the probability of the lightning-triggered electroporation influence on horizontal gene transfer and the origin of biological evolution. In the final chapter, we will also examine whether the Drake equation is the most appropriate probability model to apply to natural processes underlying the origin of life on early Earth. By considering the relevant parameters necessary for the origin of life and the sources of uncertainty in calculating the probability of the impact of lightning on prebiotic synthesis and HGT, we will try to show that this is not a purely quantitative issue but a fundamental philosophical undertaking of different possibilities.

2. Warm little pond

But if (and oh what a big if) we could conceive in some warm little pond with all sorts of ammonia and phosphoric salts, light, heat, electricity etcetera present, that a protein compound was chemically formed, ready to undergo still more complex changes (Browne, 1978).

Did evolution take place in a warm little pond? In his 1871 letter to Joseph Hooker, Charles Darwin hints at an idea that is still very relevant today. Darwin's „little pond" is a matter of a suitable environment for the origin of life, whether it is a pond, fresh or saltwater, soil, or some other environment. More importantly, all of the parameters that Darwin listed are still under intense scrutiny. Our paper also considers the necessary ranges of electricity, heat, nitrogen fixation, and phosphate reduction required for evolution to occur.

The possibility of lightning-mediated horizontal gene transfer (HGT) contributing to the origin of evolution represents the Darwinian extension of the „warm little pond" question. Various researchers from different fields have attempted to respond to Darwin's inspiring astonishment, but none has done so in such detail as Tadej Kotnik (2013).

2.1 Horizontal gene transfer (HGT)

In the introductory part, we mentioned that one of the main features of biological evolution is variation. This subsection will explain why HGT is an essential contributor to prokaryotic genetic variability. HGT is the transfer of genetic material between unicellular or multicellular organisms or DNA transfer between „ancestors“ and „descendants“. Of particular importance to HGT is the phylogenetic tree, which shows the common roots of bacteria, archaea, and eukaryotes.

Research on the transmission of genetic information is not new. It dates back to Griffith's 1928 experiment, which showed that bacteria could exchange intracellular content (Blokesch, 2016). Several mechanisms enable HGT, but we can single out three natural pathways by which DNA transfer is enabled (Kotnik, 2013: 355): (i) bacterial conjugation, (ii) natural bacterial competence for DNA uptake, and (iii) viral transduction. The fourth natural mechanism that enables horizontal gene transfer is (iv) membrane electroporation[3]. Each of these mechanisms evolved at a particular stage of evolution, but the question of a possible fourth mechanism also answers the problem of the existence of HGT prior to each of these mechanisms.

Membrane electroporation is the result of atmospheric electrostatic discharges, i.e., lightning. Several theoretical and experimental considerations support the thesis that HGT is a process triggered by lightning (Golberg, 2013; Weaver and Chizmadzhev, 2018). Before turning to the chapter on electroporation and gene transfer, it should be noted that HGT is a vital process for variability in biological evolution mentioned above. Without the mechanisms of HGT, Plant Y could not mutate successfully and would not have the advantage of spiny leaves over Plant X, which is easily digested by herbivores. HGT represents, in a sense, a primordial mechanism of natural selection. Cells whose genes acquire a proper function have a significant advantage over cells that are not so „lucky“.

2.2 Electroporation and HGT[4]

As we have already defined earlier, electroporation exposes membranes (unicellular or multicellular organisms) to electric fields of sufficient strength

---

3 Kotnik (2013) and numerous other researchers cite electrofusion as a natural HGT mechanism. However, for the purposes of this article, which focuses on probability calculations in the final section, we will focus exclusively on electroporation as a more likely mechanism that requires fewer assumptions and *ad hoc* hypotheses.

4 Behind the thesis that electroporation is a successful mechanism that enables HGT is a fascinating story about the Louisville Water Company (LWC). In 1896, the LWC investigated various methods of purifying water by killing microorganisms. On this occasion, they used high-voltage electrical pulses and discovered that this process contributed to the leakage of intracellular material, including DNA (Benton, 1896).

and conductivity (Kotnik, 2013: 355). We will explain how membrane electroporation enables the exchange of genetic material and what role water molecules play in this process. That means that electroporation and HGT depend on the aquatic environment in which they occur. The voltage ranges, measured in kV/cm, required to form transmembrane electric fields should also be considered[5]. We will also explain exactly how the pores through which HGT occurs are formed by the electric fields.

The ranges of electric fields can be divided into low, intermediate, high, and very high. In the low ranges of electric fields, formed pores are too small to allow molecular transport through the membrane. In the intermediated range, the pores only provide a temporary HGT pathway. However, they clog very quickly and interrupt HGT. In high ranges, the cells electroporate irreversibly, and the pores do not close, allowing an efficient exchange of intracellular material. However, the reason why high ranges are not optimal for HGT is also why very high ranges are optimal. This reason is thermal damage, allowing molecules to be released and DNA to melt. In very high ranges of electric fields, the temperature is high enough to cause thermal damage, and at the same time, electroporation is irreversible (*Ibid*: 357).

Thermal damage occurring in very high ranges of electric fields is characterized by pulse friction. The shorter the electrical pulse (as in the case of lightning in milliseconds), the more thermal damage is present, and electroporation successfully leads to irreversibility[6]. In aquatic environments affected by atmospheric electrostatic discharges, i.e., lightning, DNA exchange occurs between electroporated organisms, e.g., two prokaryotes without cell walls.

---

5 The field strength required for electroporation depends on the cell type; for bacteria, it varies between 3–24kV / cm, for mammalian cells, 0.25–3 kV / cm, and for plants, 3–12 kV / cm (Kumar et al., 2019).

6 Reversible electroporation is also considered an efficient mechanism for eukaryotic transformation (Kotnik, 2017). However, for the same reasons that we focused on electroporation rather than electrofusion, we will focus on irreversible rather than reversible electroporation. To calculate the probability, we will attempt to minimize the number of assumptions necessary for the possibility that HGT is a lightning-triggered process.

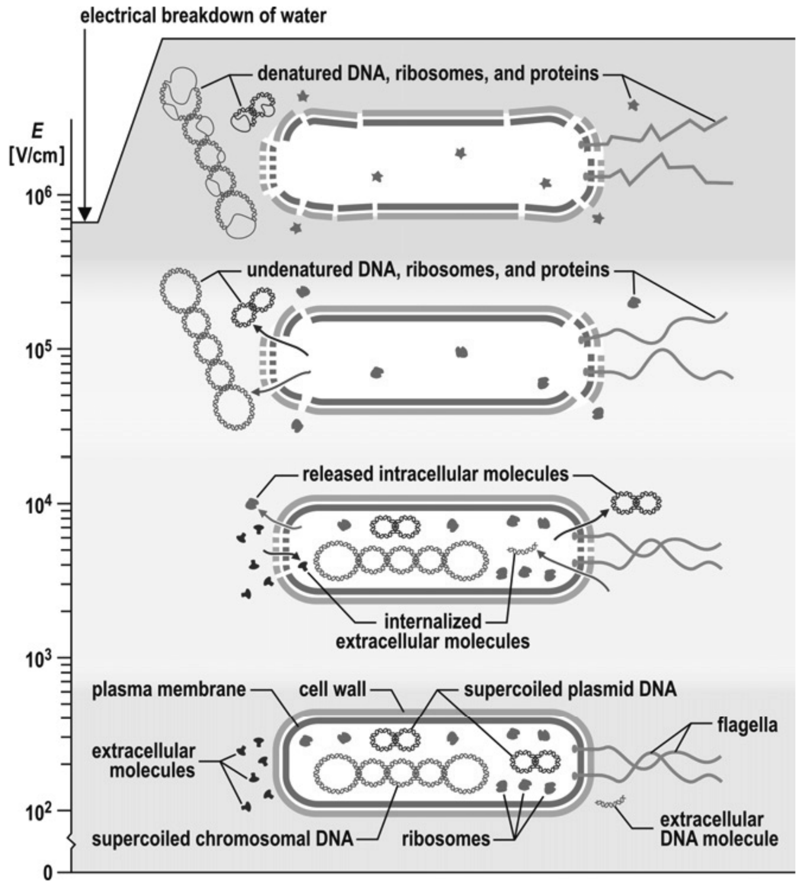

Figure 1. Electroporation-mediated molecular transport as a function of the external electric field – lightning (Kotnik, 2013: 356).

It should be noted that the vast majority of lightning is negatively classified, while only one-tenth are positive. Negative lightning occurs in sequences where the first stroke is most vigorous and originates mainly from the lower parts of the clouds, while positive lightning consists of a single stroke from the upper part of the cloud. Nag and collegues (2015) shows that the electrical currents range from 80 to 250 kA for 5–20 microseconds. That indicates that the first negative lightning strike could meet the required duration and electric current levels for lightning-triggered HGT to occur without DNA melting or rapid cell pore closure.

Considering rainwater, rivers, oceans, and lakes, it is necessary to single out the aquatic properties that HGT requires to be successful due to lightning strikes. When we talk about aquatic environments, we should pay attention to the type of water in question. Different aquatic environments have different electrical conductivities. Saltwater stimulates conductivity, but not the same degree as shallow and small ponds. In addition to conductivity, shallow and small ponds have more affluent populations of prokaryotes (Kotnik, 2013:

364). That favorable aquatic environments, electric field ranges, lightning strikes, and thermal DNA denaturation are not merely theoretical speculations is shown by the studies of Park and collegues (2013) on *Escherichia coli* and *Salmonella typhimurium* and Lee and collegues (2021) on *Pseudomonas aeruginosa*.

To conclude this chapter, it is essential to point out that theoretical considerations about HGT as lightning-triggered are supported by empirical research on the same phenomenon. Experimental conditions that simulate the environment of early Earth conditions must be finely nuanced to demonstrate the plausibility of theoretical hypotheses that would otherwise be mere fantasies at the long stick. One indicator of this research dynamic is the Miller-Urey experiment, which we will discuss in more detail in the next chapter.

Eruption of evolution

If we remove ancient cosmology from its anecdotal-mystical context and synchronize it with paradigm shifts in the life sciences, astrobiology, and prebiotic chemistry, we will find that Anaxagoras and Empedocles were not so far from the truth. Many pre-Socratic philosophers were guided by the idea that the entire universe, including our planet, is in constant pulsation. Natural events such as the tides, the alternation of day and night, and the recurring eruptions of volcanic geysers constantly give rise to new molecules and chemical systems through the processes from which they emerge. Molecules and systems become more complex and develop new properties as they interact with the environment. Simply put, they create life!

3.1 Fatty acids: bridging the gap between chemical and biological evolution

For illustrative purposes, we can take a fatty acid that consists of carbon, hydrogen, and oxygen atoms. As a group of atoms arranged in a specific pattern, fatty acid is just one of the complex molecules essential to living cells. Scientists believed that only cells could build fatty acids, but experiments conducted under controlled laboratory conditions provide new insights (Morigaki and Walde, 2007).

When simple gases, such as carbon monoxide and hydrogen, are heated with minerals in the earth's mantle, more complex carbon molecules such as fatty acids begin to form. That implies that living cells are not necessary for the emergence of chemical evolution but that there is a possibility that life may have originated in subsurface chambers using volcanic magma as a heat source (Van Gaever et al., 2009). As pressure increases, molecules rise into a water basin above the subterranean chambers, where a simplified version of natural selection takes control, as nature „decides" which molecules remain in the aquatic environment and which sink. Volcanic magma heats water in which fatty acids accumulate due to the attraction between oxygen and water molecules. On the other hand, the carbon in fatty acids repels water molecules. This dynamic of repulsion and attraction causes the fatty acids to collide with their „tails" in the procession, forming a sphere. The result of this process is a stable, hollow vessel that resembles a membrane and represents an entirely new environment in which chemical evolution takes place[7].

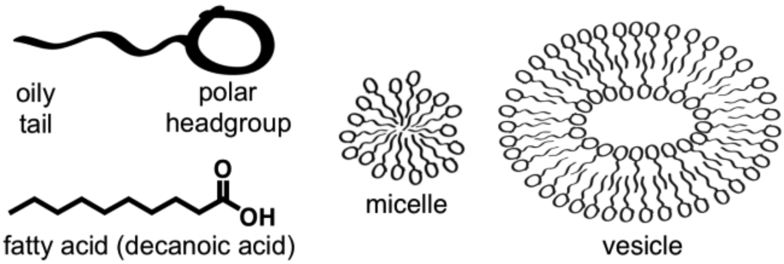

Figure 2. Fatty acid self-assemble into micelles and bilayer vesicles that resemble cell membranes (Black and Blosser, 2016: 4).

It is essential to point out that membranes formed from fatty acids cannot be classified as „living" because, unlike living cells, they do not have the possibility of reproduction. That is very important because it shows that chemical evolution can, through further development, create new properties, environments, and systems that are fully reproducible. This transition from inanimate to living membranes or cells bridges the gap between chemical and biological evolution and represents a significant advance in life sciences.

3.2 Nitrogen and phosphorus

Nitrogen and phosphorus are fundamental elements for the origin of life, as they enable prebiotic synthesis. Nitrogen is found in proteins, enzymes, ribosomes, ATP, RNA, and DNA (Vitousek et al., 2002), while phosphorus is also found in ribosomes, ATP, RNA, and DNA molecules (Tiessen, 2008).

Prebiotic synthesis, or abiogenesis, combines molecules into more complex structures capable of independent reproduction. For that reason, prebiotic synthesis is crucial for chemical and biological evolution. Nitrogen, an essential element for processes such as cell division and morphogenesis, must be converted to hydrogen cyanide, ammonia, or nitrate to participate in prebiotic synthesis. For this to happen, nitrogen fixation, which allows nitrogen as an inert gas to chemically interact with other elements, must

7 The first membranes are composed of simple amphiphiles, i.e., fatty acids consisting of tails (hydrocarbon chains) and heads (carboxyl groups) forming water vesicles. Prebiotic fatty acids are spontaneously assembled into compartments that look like cells and have the capacity for growth (Black and Blosser, 2016: 4).

occur (Vitousek et al., 2002). On the other hand, phosphorus is essential for cell structure and its functions and must be reduced to hydrophosphites or phosphites to be eligible for prebiotic synthesis (Tiessen, 2008).

Atmospheric models show that significant amounts of nitrogen were present in the early Earth's atmosphere in the form of the inert gas – molecular nitrogen. Also, phosphorus was naturally present in the form of, both, the insoluble mineral *apatite* and the unusual mineral, *schreibersite*, found in meteorites. Experiments have revealed that schreibersite can disband in water to create hydrophosphites, which in turn react to assemble organic molecules essential for the origin of life (Walton et al., 2021).

3.3 Frankenstein's monster from the volcano

We have already mentioned that volcanic magma is a vital source of energy in underground chambers where chemical evolution occurs. Alongside that, even more interesting is the multifaceted influence of volcanoes on the origin of chemical evolution and life on the early Earth.

Navarro-González and Segura (2004) show how the impact of lightning can produce hydrogen cyanide and ammonia through nitrogen fixation. And not just any lightning, but electrostatic discharges from volcanic clouds. The same goes for the phosphate reduction that results from fulgurite formation due to the impact of volcanic lightning. Fulgurite is a hollow, glassy tube that forms in quartz sand (fossilized lightning). Significant amounts of schreibersite and other reactive phosphorus minerals can be found in fulgurite (Pasek and Block, 2009).

Clouds of volcanic ash and gas, where all the prebiotic components necessary for the origin of life are present, are suitable environment for synthesizing organic molecules (Navarro-González and Segura, 2004: 139). Volcanic ash contains minerals with sufficient surface area and catalytic properties, while volcanic clouds produce sufficient temperature and electrostatic discharge force as efficient energy sources. Both experimental studies and theoretical considerations suggest that lightning from volcanic clouds during high-explosive eruptions could be an essential source of reactive nitrogen and phosphorus, and thus chemical evolution (Navarro-González and Segura, 2004: 140).

Thermohistorical models show that volcanic activity of the early Earth was very intense, producing large amounts of lava and pyroclastics annually (Herzberg et al., 2010). Volcanoes emit physical properties in the form of gases, liquids, and solids, all of which are very important for prebiotic synthesis. Magmatic processes, where volatiles dissolve and magma is decompressed, and hydromagmatic processes, where liquid or ice comes into contact with lava, create environments where large amounts of gases and hot solid fragments are present. This further contributes to the formation of exhaust gases and airfall fragments that culminate in intense lightning activity from explosive volcanoes.

During these eruptive episodes, the pyroclastic and magmatic gases generate strong electric fields and photochemical processes that simulate a natural chemical reactor (Navarro-González and Segura, 2004: 141–143).

Parameters such as the individual variety of gases present in a volcano, the temperature and pressure, the strength of the electric fields, and the range of energy dissipation lead to the generation of different types of lightning: intracloud, cloud-to-ground, ground-to-cloud, and air discharges. Focusing on cloud-to-ground volcanic lightning and its properties, we can explain the origin of nitrogen fixation and phosphate reduction. Assuming that the early Earth's atmosphere was 80% carbon dioxide and 20% molecular nitrogen, Navarro-González (1998) showed that lightning fixes nitrogen, in experimental studies of Hawaiian volcanoes[8]. On the other hand, Pasek (2008) showed that the heating of apatite minerals and other minerals from volcanic environment, by lightning strikes, leads to polyphosphate formation.

To conclude this chapter, we must point out that theoretically severe considerations and conceptual barriers accompany the above experimental studies. In the next chapter, we will show what parameters and sources of uncertainty can be considered when calculating the probability of the influence of lightning on HGT and the prebiotic synthesis.

4. The truth is out there? Guidance from the Drake equation

> As I planned the meeting, I realized a few day[s] ahead of time we needed an agenda. And so I wrote down all the things you needed to know to predict how hard it's going to be to detect extraterrestrial life. And looking at them it became pretty evident that if you multiplied all these together, you got a number, N, which is the number of detectable civilizations in our galaxy. This was aimed at the radio search, and not to search for primordial or primitive life forms.
>
> —Frank Drake

In 1961, American astronomer and astrophysicist Frank Drake formulated an unusual equation. Although the equation calculates the number of interplanetary civilizations capable of communicating within the Milky Way, it was initially a semi-parody or approximation. Drake intended his equation to promote scientific dialogue at the first SETI[9] conference. Drake's equation can be represented as follows:

8 Due to the considerations that will be mentioned later in the paper, we must note here that the assumed composition of the Early Earth's atmosphere in the Miller-Urey experiment is completely different. In this experiment, the composition of the Early Earth's atmosphere is greatly reduced. The Miller-Urey experimental error will also be significant for dealing with key philosophical issues of parameter choice when calculating probabilities in evolutionary domains.

9 Search for extraterrestrial intelligence, or SETI is the collective term for the search for extraterrestrial life. The need to communicate with extraterrestrial organisms is as old as the idea of the possibility of life existing „somewhere out there." However, with advances

$$N = R_{*} f_{p} n_{p} f_{l} f_{i} f_{c} L,$$

where, N represents the number of civilizations that are detectable by electromagnetic emission, R_{*} is the formation rate of the corresponding stars, f_p is the fraction with planetary systems, n_p is the number of planets in such systems suitable for life, f_l is the fraction at which life actually develops, f_i is the fraction with the planets on which intelligent life can occur, f_c is the fraction of the planets that developed a civilization with the necessary signal detection technology and L is the time frame during which these civilizations emit such signals (Ćirković, 2004).

A glance at the literature shows that Drake's equation has received much more criticism than scientific and reasoned support. On the other hand, with the same insight, we come to a vast number of papers and research that show that the promotion of scientific debate, as Drake's original motivation, was a great success. We can talk about the usefulness of the Drake equation from different perspectives. Some have taken it seriously, others as a parody. Nevertheless, the fact is that Drake's equation has a wide application (or at least attempts to do so) outside the field in which it originated. It also has an application within the subject of our work, which we will present in the following subsection.

4.1 Drake equation and the lightning-triggered electroporation

In the second chapter, we presented a detailed theoretical and experimental contribution by Tadej Kotnik on lightning-triggered electroporation as a possible contributor to HGT. At the same time we previosly hinted at the application of the Drake equation outside the astrophysical domain from which it originated. One such application is James Weaver's (2013) attempt to replicate Kotnik's assumptions and calculate the probability of HGT as a lightning-triggered process.

At the risk of repeating ourselves, it is necessary to highlight the main parameters of Kotnik's considerations to understand the basis on which Weaver formulated a specific application of the Drake equation. The primary phenomenon is the generation of electric current density J in the aquatic environment. A widely distributed J results in electric fields that can electroporate prokaryotic membranes. Based on pulse strength, duration, and repeatability, there are three possible outcomes: lethal, HGT possible, and no EP effect (Weaver, 2013: 374). The near-ideal candidate for the necessary energy source is lightning, which has not changed significantly over time in evolutionary terms. Other parameters include global lightning and the

---

in technology and means of electromagnetic radiation detecting distant civilizations, it has also become somewhat institutionalized (Dick, 2020). As a curiosity, we can highlight Nikola Tesla's unusual idea in 1896 to make contact with Mars using a wireless electrical transmission system.

evolutionary time frame in which HGT was important. Weaver finally arrives at the following reformulation of the Drake equation:

$$N_{HGT} = R_{LST} n_{BAC} V_{EPZ} f_{EPT} f_{SIG} L_{HGT},$$

where N_{HGT} is the total number of evolutionarily significant changes due to lightning, R_{LST} is the rate of lightning strikes on the early Earth, n_{BAC} is the bacterial concentration in the environment, V_{EPZ} is the volume of the zone with successful electroporation, f_{EPT} is the fraction of successfully electroporated bacteria, f_{SIG} is the test value for a fraction of porous cells undergoing evolutionarily significant HGT, and L_{HGT} is the time during which evolutionarily significant changes occur (*Ibid*: 375).

Attempts to salvage Drake's equation as plausible and practical consist of conceptual-statistical arguments. Drake's equation is a mere average rate, but it can help identify essential parameters and highlight sources of uncertainty in the calculation of some evolutionary problems. This case can help isolate important processes for the lightning-triggered HGT and the rather sensitive N_{HGT} value as a source of uncertainty. From our case's average rate statistic nature, it is clear that the total number of evolutionarily significant changes caused by lightning will be pretty large. Weaver correlates N_{HGT} and f_{SIG} to reduce the enormous number of evolutionary changes and counterargument himself. The test value for a fraction of porous cells participating in evolutionarily significant HGT would be really-really small for only a few significant HGT occurrences (Weaver, 2013: 375). Furthermore, since experiments readily show how electroporation triggered by lightning can cause HGT, one can conclude that N_{HGT} remains large valued. If there is no conceptual problem (which we will discuss in the next chapter) with the choice of parameters for applying Drake's equation, then Weaver successfully shows a high probability of the influence of lightning on the HGT emergence.

4.2 Drake equation and lightning-triggered prebiotic synthesis

In the previous part of the paper, we explained the symmetrical similarities between the origin of chemical and biological evolution. We presented Kotnik's experimental and theoretical arguments for lightning-triggered HGT and Navarro-González's considerations on the influence of volcanic lightning on the occurrence of prebiotic synthesis. We then presented Weaver's attempt to apply the Drake equation to parameters that Kotnik elaborated as significant for lightning-triggered HGT. The similarity between Kotnik and Navarro-González in isolating lightning as a potential contributor to evolution and life on the early Earth and Weaver's application of the Drake equation in calculating lightning-triggered HGT probabilities provide an argumentative basis for applying the Drake equation to the origin of prebiotic synthesis. Our reformulation of Drake's equation would be as follows:

$$N_{PBS} = R_{VLS} n_{DNC} n_{PVS} V_{SOM} f_{NFX} f_{PHR} f_{SIG} L_{PBS},$$

where N_{PBS} is the total number of evolutionarily significant changes caused by volcanic lightning, R_{VLS} is the rate of volcanic lightning strikes on the early Earth, n_{DNC} is the concentration of molecular nitrogen in the early atmosphere and n_{PVS} is phosphite saturation in volcanic minerals, V_{SOM} is the volume zone of successful synthesis of organic molecules, f_{NFX} is a fraction of successful nitrogen fixation and f_{PHR} is a fraction of successful phosphate reduction, f_{SIG} is the test value for a fraction of molecules undergoing evolutionarily significant prebiotic synthesis, and L_{PBS} is the time during which evolutionarily significant changes occur.

We emphasized earlier that the Drake equation, in statistical terms, is just an average rate. That means that N_{PBS}, with its enormous value, will be a source of uncertainty even in this case. To make our assignment a bit harsher, we will again correlate N_{PBS} and f_{SIG}. The test value for a fraction of molecules undergoing evolutionarily significant synthesis would be minimal for just a few significant volcanic lightning occurrences. Numerous theoretical considerations, followed by Navarro-González's experiments on Hawaiian volcanoes similar to the primordial magmatic environments of the early Earth, offer solidly backed-up evidence that prebiotic synthesis is caused by volcanic lightning. We can conclude that the value of N_{PBS} will remain relatively high and that the Drake equation also proved successful in solving the evolutionary problems of our case.

However, our „Drake" chapter is under a big „if". The ground of our „probabilistic project" lies on a conceptual slide of proper selection of parameters relevant to the origin of life on the early Earth and efficient determination of the sources of uncertainty. A thorough examination and methodological tuning are necessary prerequisites for calculating the probability of the influence of lightning's impact on chemical and biological evolution. In the next chapter, we will address these conceptual obstacles and attempt to argue that the problem of probability in the life sciences is fundamentally a philosophical issue and not a purely quantitative project.

5. Concluding remarks

In the previous chapter, we presented the basic features of the Drake equation (DE), Weaver's application of DE to the probability of HGT as a lightning-triggered process, and our application of DE to the probability of prebiotic synthesis as a volcanic lightning process. We highlighted the conceptual elements in DE, such as selecting relevant parameters for the emergence of chemical and biological evolution on the early Earth and determining the sources of uncertainty in calculating probabilities in the life sciences. In this chapter, to further clarify these conceptual hurdles, we will introduce the Miller-Urey experiment and Hess's (2021) estimation of the amount of *fulgurite* on the early Earth. Finally, we will show why relevant parameters and sources of uncertainty are problems that philosophers can answer and provide furder guidelines for using different types of probabilities in life sciences.

5.1 About parameters: Miller-Urey experiment

Several recurring phenomena link Kotnik's and Navarro-González's research. In addition to lightning, which both consider a cause of evolution, there is also part of their research on fatty acids and lipid bilayers and a reference to the Miller-Urey experiment, which is a vital starting point for both authors.

Stanley Miller, a chemist at the University of Chicago, conducted the first experiment in the 1950s to produce amino acids and protein building blocks from inorganic molecules and electricity (McColl, 2013). Miller's students discovered many new organic molecules based on their mentor's experiment and showed that the standard experiment performed by Miller, although never published, offered the best guidance to the origin of life on Earth before 4 Gyr.

The classic Miller-Urey experiment uses a mixture of gases and water in a proportion that Miller assumed was present on the early Earth. This mixture was later subjected to a specific temperature and electrical current fluctuations to simulate a lightning strike. In this way, Miller could generate and identify five different amino acids (Ibid: 207–210). The secondary setting of this experiment is called the „volcanic apparatus," in which new 22 amino acids were generated and identified (Parker et al., 2014).

The volcanic apparatus differs only in minor details from the classical experiment, although these details make a big difference. Narrowing one of the glass tubes increases the flow of water vapor through which the electrical current flows. This slight variation and reconfiguration of the experiment results in a more decadent combination of amino acids and produces new amino acids that had not been discovered in any other simulated early Earth experiment. In addition, many of the newly discovered amino acids have hydroxyl groups, making them more reactive and prone to forming new molecules over more extended periods (*Ibid*: 2–5).

One of the main criticisms of Miller's experiment is that he did not use all the relevant parameters related to the atmosphere of the early Earth (Ibid: 5–8). The initial conditions in Miller's experiments did not simulate the entire surface of the early Earth, so replication is questionable. From this, it is clear why the conceptual hurdle in selecting relevant parameters is fundamental to research in the life sciences. A small error can lead to significant discrepancies in results and replication. However, the case of the Miller-Urey experiment is fascinating because it was this oversight that steered research in an entirely new direction.

Although it is questionable whether Miller's experiments faithfully replicate the „entire" surface of the early Earth, it undoubtedly simulates conditions that could be found in some smaller regions of the planet. Miller's ratio of gasses to water could be emitted from many volcanoes present on the early Earth at that time. The necessary energy source would be the volcanic lightning accompanying magmatic eruptions. A little extra water vapor in the „volcanic apparatus" makes a big difference, which brings us to Navarro-González's research. In the same way water vapor deflects amino acids from sparks before they react and form other compounds, volcanic ash and gas clouds quickly remove organic molecules from the reaction zone. Finally, we conclude the Miller-Urey story on the conceptual importance of selecting relevant parameters by pointing out that new modifications to the volcanic apparatus could be a good simulation indicator of life conditions on early Mars and Titan. At the same time, current developments in instruments and technologies could provide insights into amino acids beneath the surface of the Red Planet (Petrescu et al., 2018).

5.2 About uncertainty: estimating fulgurite amounts

We have noted that the advantage of the Drake's equation is that it highlights the source of uncertainty in calculating probabilities in evolutionary problems. However, there are other types of probabilities that we can use in the life sciences that can even more successfully locate the sources of uncertainty and highlight the relevance of some parameters. To consider probabilities as an alternative to the Drake's equation, we will first introduce a calculation that goes back to early Earth and is not a complex average rate subject to hanging uncertainties.

In the part of our paper devoted to volcanic lightning as a possible contribution to the origin of chemical evolution, we mentioned the importance of the elements nitrogen and phosphorus. In order to enter into prebiotic synthesis, phosphorus must be reduced. Sources of phosphorus on the early Earth could be found in the form of the natural mineral *apatite* but also the form of the unusual meteorite mineral *schreibersite*. One of the arguments in favor of the influence of lightning on the formation of reactive phosphorus is the mineral *fulgurite*, also called „petrified lightning". Inside *fulgurite*, a hollow glass tube formed in quartz sand, we find significant amounts of *schreibersite*.

To determine whether lightning affected *schreibersite* formation, scientists tried to estimate the amount of phosphorus produced by lightning strikes from 4.5 Gyr, when Earth came into existence, to 3.5 Gyr when the earliest fossils evidence of the living world was found (Hess et al., 2021). To accomplish this unusual task, geologists had to estimate three things: the number of *fulgurites* formed each year, the amount of phosphorus in the rocks of the early Earth, and how much of that phosphorus was rendered usable by lightning strikes. *Fulgurites* form when lightning hits the ground. Therefore, the first step was to estimate the number of lightning strikes. This number can be determined by estimating the amount of carbon dioxide in the early Earth's atmosphere and the number of lightning strikes for different amounts of carbon dioxide. Estimating the amount of CO_2 in the atmosphere is a reliable indicator for estimating global temperature, a critical factor in estimating the frequency of thunderstorms (Hess et al., 1–3).

Using these variables, geologic models show that one hundred million to one billion lightning bolts struck the early Earth each year, with each bolt forming a *fulgurite*. In the first Gyr of Earth's history, up to a quintillion (1 ... 18 zero) *fulgurites* formed (Ibid: 4). The Hawaiian islands and volcanoes most closely represent the conditions of life on the early Earth. Therefore, the basaltic rocks of Hawaii were used to determine the average phosphorus content in rocks that were prevalent in the early Earth. By combining these factors, it was calculated that lightning strikes, on the annual level, produced more than ten tons of phosphorus that could be used for organic reactions. This means that lightning produced about as much phosphorus as meteorites, i.e., it produced all the phosphorus necessary for the origin of life on Earth (*Ibid*: 6).

Further research guidelines

We have presented specific examples where selecting relevant parameters can steer the research in a completely new direction and make significant differences in terms of results. We have also shown that determining the source of uncertainty in some evolutionary problems can be an appropriate criterion for selecting the type of probability that we will apply. To conclude our paper, we will present several criticisms of the applicability of the Drake equation to evolutionary problems and probabilities of cosmological proportions, and suggest some other potential candidates that would be more appropriate for the temporal context of Gyr magnitude.

One of the more interesting critiques of the Drake equation is Fermi's famous paradox[10] that asks, „How many piano tuners are there in Chicago?" (Prantzos, 2013). The parameters included in the average rate callculations are: five million people live in Chicago, on average two people live in a household, one in twenty households owns a piano, pianos need to be tuned once a year, it takes the piano tuner two hours to travel to a household and tune the piano, with each piano tuner working eight hours per day, five days per week, and 50 weeks per year. Based on these parameters and the estimated rate, there are 125 thousand piano tunings in Chicago per year or one thousand piano tunings per tuner per year. So there are 125 piano tuners in Chicago (Prantzos, 2013: 246–248).

---

10 I want to thank Professor Milan Ćirković of the Astronomical Observatory in Belgrade, who pointed me to this example and gave helpful comments on problems with the Drake equation during the *Sciences of the Origin: The Challenges of Selection Effects and Biases conference* (June 3–5, 2021).

The Drake equation is a modification of the Fermi problem in which we use the multiplication of parameters to determine the average rate of communicative civilizations in the Milky Way. The money-shoot question here is: if the abundance of civilizations can communicate within our galaxy, why have we not contacted them yet? This mesmerizing puzzle is called the *Fermi paradox*. The mere fact that the estimated number of existing civilizations capable of communication in the Milky Way is quite large and that the inhabitants of Earth, who are also capable of communication, have not yet made contact with their undersized purple neighbors (or whatever they look like) indicates that there is something wrong with this probability calculation. The issue is not the shortcomings of the formula itself but the suitability of its application to this kind of problem. Tuning a piano in Chicago is not the same as estimating the number of intelligent civilizations in the Milky Way. The application problem reduces to the lack of temporal structure and appreciation of the importance of evolutionary effects pointed out by Ćirković (2004).

In our case, things are a bit different. We cannot ask, „If the probability of lightning-triggered evolution is so great, why has evolution not occurred yet?“ Evolution has undoubtedly occurred; otherwise, we would not be so late in submitting this article to the *Belgrade Philosophical Annual*. However, the question here cannot be posted in the form of „if-then“, but „if not – then what?“. Schultheis (2020), Byrne and Johnson-Laird (2020), and Stalnaker (2021) have written about more detailed approaches to counterfactual probabilities as a possible digression of complicated statistical calculations into no less complex philosophical and sociological considerations.

The key philosophical issues of applying Drake's equation to the calculation of probability in evolutionary domains are based on the sources of uncertainty and the methodology for selecting appropriate parameters. In the Miller-Urey experiment, we showed that a small error in parameter selection could make a huge difference in the results of the phenomenon we are examining. In contrast, in an anecdotal example of a piano tuner, we showed that the average probability rate could not be applied with the same enthusiasm to the Chicago population and the vast number of habitable planets in the universe. The choice of possible types of probability calculations depends on many factors, which become especially important when dealing with data-rich contexts, cosmological timescales, and sources of uncertainty that lead to significant discrepancies in results. On the other hand, Bayesian probability theory incorporates sources of uncertainty much better into its formulas and considers research information gaps and blind spots much more carefully (Scharf and Cronin, 2016; Grimaldi and Marcy, 2018). Insights from the philosophy and sociology of science come to the fore, especially in this kind of research framework and „almost-metaphysical“ contexts. In any case, there is no shortage of questions in the life sciences, problems are still visibly unresolved and cascading, and it is up to philosophers to get into the game and try to contribute to new insights and methodological and conceptual pedantry.

References:

Benton, G. W. (1896). Louisville Filtration Experiments. In *Proceedings of the Indiana Academy of Science* (Vol. 6, pp. 63–65).

Black, R. A., & Blosser, M. C. (2016). A self-assembled aggregate composed of a fatty acid membrane and the building blocks of biological polymers provides a first step in the emergence of protocells. *Life*, *6*(3), 33.

Blokesch, M. (2016). Natural competence for transformation. *Current Biology*, *26*(21), R1126-R1130.

Browne, J. (1978). The Charles Darwin—Joseph Hooker correspondence: an analysis of manuscript resources and their use in biography. *Journal of the Society for the Bibliography of Natural History*, *8*(4), 351–366.

Byrne, R. M., & Johnson-Laird, P. N. (2020). If and or: Real and counterfactual possibilities in their truth and probability. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *46*(4), 760.

Ćirković, M. M. (2004). The temporal aspect of the Drake equation and SETI. *Astrobiology*, *4*(2), 225–231.

Dick, S. J. (2020). Consequences of Success in SETI: Lessons from the History of Science. In *Space, Time, and Aliens* (pp. 129–142). Springer, Cham.

Golberg, A. (2013). The impact of pulsed electric fields on cells and biomolecules: Comment on "Lightning-triggered electroporation and electrofusion as possible contributors to natural horizontal gene transfer" by Tadej Kotnik. *Physics of Life Reviews*, *10*(3), 382–383.

Grimaldi, C., & Marcy, G. W. (2018). Bayesian approach to SETI. *Proceedings of the National Academy of Sciences*, *115*(42), E9755-E9764.

Herzberg, C., Condie, K., & Korenaga, J. (2010). Thermal history of the Earth and its petrological expression. *Earth and Planetary Science Letters*, *292*(1–2), 79–88.

Hess, B. L., Piazolo, S., & Harvey, J. (2021). Lightning strikes as a major facilitator of prebiotic phosphorus reduction on early Earth. *Nature communications*, *12*(1), 1–8.

Kotnik, T. (2013). Lightning-triggered electroporation and electrofusion as possible contributors to natural horizontal gene transfer. *Physics of life reviews*, *10*(3), 351–370.

Kotnik, T. (2017). Lightning-triggered electroporation as a mechanism for horizontal gene transfer. *Handbook of electroporation. Springer, Cham*, 369–385.

Kumar, P., Nagarajan, A., & Uchil, P. D. (2019). Electroporation. *Cold Spring Harbor Protocols*, *2019*(7), pdb-top096271.

Lee, I. P. A., Eldakar, O. T., Gogarten, J. P., & Andam, C. P. (2021). Bacterial cooperation through horizontal gene transfer. *Trends in Ecology & Evolution*.

McCollom, T. M. (2013). Miller-Urey and beyond: what have we learned about prebiotic organic synthesis reactions in the past 60 years?. *Annual Review of Earth and Planetary Sciences*, *41*, 207–229.

Morigaki, K., & Walde, P. (2007). Fatty acid vesicles. *Current Opinion in Colloid & Interface Science*, *12*(2), 75–80.

Nag, A., Murphy, M. J., Schulz, W., & Cummins, K. L. (2015). Lightning locating systems: Insights on characteristics and validation techniques. *Earth and Space Science*, *2*(4), 65–93.

Navarro-González, R., & Segura, A. (2004). The possible role of volcanic lightning in chemical evolution. In *Origins* (pp. 139–152). Springer, Dordrecht.

Navarro-González, R., Molina, M. J., & Molina, L. T. (1998). Nitrogen fixation by volcanic lightning in the early Earth. *Geophysical Research Letters*, *25*(16), 3123–3126.

Obeso, J. R. (1997). Costs of reproduction in Ilex aquifolium: effects at tree, branch and leaf levels. *Journal of Ecology*, 159–166.

Papale, F. (2021). Evolution by means of natural selection without reproduction: revamping Lewontin's account. *Synthese*, *198*(11), 10429–10455.

Park, I. K., & Kang, D. H. (2013). Effect of electropermeabilization by ohmic heating for inactivation of Escherichia coli O157: H7, Salmonella enterica serovar Typhimurium, and Listeria monocytogenes in buffered peptone water and apple juice. *Applied and environmental microbiology*, *79*(23), 7122–7129.

Parker, E. T., Cleaves, J. H., Burton, A. S., Glavin, D. P., Dworkin, J. P., Zhou, M., ... & Fernández, F. M. (2014). Conducting miller-urey experiments. *JoVE (Journal of Visualized Experiments)*, (83), e51039.

Pasek, M. A. (2008). Rethinking early Earth phosphorus geochemistry. *Proceedings of the National Academy of Sciences*, *105*(3), 853–858.

Pasek, M., & Block, K. (2009). Lightning-induced reduction of phosphorus oxidation state. *Nature Geoscience*, *2*(8), 553–556.

Petrescu, R. V., Aversa, R., Apicella, A., & Petrescu, F. I. (2018). Nasa selects concepts for a new mission to titan, the moon of saturn. *Journal of Aircraft and Spacecraft Technology*, *2*(1), 40–52.

Prantzos, N. (2013). A joint analysis of the Drake equation and the Fermi paradox. *International Journal of Astrobiology*, *12*(3), 246–253.

Rauchfuss, H. (2008). *Chemical evolution and the origin of life*. Springer Science & Business Media.

Ruiz-Mirazo, K., Briones, C., & de la Escosura, A. (2017). Chemical roots of biological evolution: the origins of life as a process of development of autonomous functional systems. *Open Biology*, *7*(4), 170050.

Scharf, C., & Cronin, L. (2016). Quantifying the origins of life on a planetary scale. *Proceedings of the National Academy of Sciences*, *113*(29), 8127–8132.

Schultheis, G. (2020). Counterfactual probability. *Manuscript, University of Chicago*.

Sober, E. (2006). *Filozofija biologije*. Beograd: Plato.

Stalnaker, R. (2021). Counterfactuals and Probability. *Conditionals, Paradox, and Probability: Themes from the Philosophy of Dorothy Edgington*, 100.

Tiessen, H. (2008). Phosphorus in the global environment. In *The ecophysiology of plant-phosphorus interactions* (pp. 1–7). Springer, Dordrecht.

Van Gaever, S., Moodley, L., Pasotti, F., Houtekamer, M., Middelburg, J. J., Danovaro, R., & Vanreusel, A. (2009). Trophic specialisation of metazoan meiofauna at the Håkon Mosby Mud Volcano: fatty acid biomarker isotope evidence. *Marine Biology*, *156*(6), 1289–1296.

Vitousek, P. M., Hättenschwiler, S., Olander, L., & Allison, S. (2002). Nitrogen and nature. *AMBIO: A Journal of the Human Environment*, *31*(2), 97–101.

Walton, C. R., Shorttle, O., Jenner, F. E., Williams, H. M., Golden, J., Morrison, S. M., ... & Pasek, M. (2021). Phosphorus mineral evolution and prebiotic chemistry: From minerals to microbes. *Earth-Science Reviews*, *221*, 103806.

Weaver, J. C. (2013). Estimating the contribution of lightning to microbial evolution: guidance from the Drake equation. Comment on "Lightning-triggered electroporation and electrofusion as possible contributors to natural horizontal gene transfer" by Tadej Kotnik. *Physics of Life Reviews*, *10*(3), 373–376.

Weaver, J. C., & Chizmadzhev, Y. (2018). Electroporation. In *Biological and medical aspects of electromagnetic fields* (pp. 243–284). CRC Press.