

Testing the Drake Equation in the Solar System

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Abstract. We suggest that the search for life on the Galilean satellites can provide a first step towards a preliminary insight into the distribution of life in the universe. Let f_i denote the usual parameter in the Drake Equation for the fraction of life-bearing planets, or satellites, where biological evolution produces an intelligent species. Then, we suggest the equation: $f_i = kf_e$. In our notation k is a constant of proportionality; it is the product of a few factors, which we need not specify here; f_e denotes the fraction of planets, or satellites, where eukaryogenesis occurs. Our conjecture motivates the search in our solar system, particularly on Europa, for a hint that the key factor in the evolutionary pathway that leads to intelligence, f_e , is non-vanishing in at least one extraterrestrial environment.

1. Introduction

It has repeatedly been said that nothing makes sense in biology, unless it is seen in the light of Darwinian evolution. Now that one of its most exciting subdisciplines (astrobiology) is in the process of being consolidated, it seems natural to reformulate age-old questions in an evolutionary context. This is one of the main purposes of the present work. Indeed, we may divide the subject of astrobiology into three parts, partly to emphasize distinct aspects in which its scientific bases are on different footing. Parts 1 and 2 correspond to the origin and evolution of life in the universe. They are supported by the fields of chemical evolution and Darwin's theory of evolution, respectively. Both of these topics are time-honored subdisciplines of astrobiology. The third aspect of astrobiology, the distribution of life in the universe and the space technologies used to address the search for extraterrestrial life, still lacks an underlying theory. In the evolution of life we discuss the transition from a simple prokaryotic blueprint of the Archean to the first appearance of the nucleated cell ("eukaryogenesis"), an event which possibly also occurred in the Archean (Brocks *et al.* 1999).

We have attempted to show that eukaryogenesis was probably the most transcendental step in the pathway that led from bacteria to human beings (Chela-Flores 1998a-c). Once eukaryogenesis took place on Earth, the steps

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leading up to multicellularity were inevitable, namely, cell signalling and the organization into cooperative assemblies (tissues).

The onset of multicellularity is essentially due to the considerably larger genomes that were compatible with the eukaryotic blueprint. The densely packaged chromosomes in the cellular nucleus presented multiple options for opportunistic ways of passing genes to progeny, some of which allowed their carriers to be better adapted to the environment. Mitosis was a more advanced process of cellular division than simple prokaryotic fission. Such variety of options were the raw material for natural selection to improve upon the 3-billion-year-old single-cell strategy of life on Earth. The improvement was achieved within 30% of the single-cell “era.” A full-organism strategy led subsequently to large-brained organisms and intelligence. The first neurone could not arise at the prokaryotic level of development. A complex pattern of gene expression is required for a functional neurone; consequently, the first stage of a nervous system had to wait for the eukaryotic threshold to be crossed. The superior strategy of translation of the genetic message of nucleated cells permitted a variety of proteins to be inserted into the cellular membrane. This new stage in evolution provided all the channels necessary for the underlying alteration of the ion concentration inside and outside the cell.

The details of the first steps towards multicellularity are not known in detail, but it is evident that in the struggle for survival, evolutionary pressures were going to encourage cells whose genomes codified proteins for cell signalling, as well as proteins that favored the formation of tissues of primitive multicellular organisms. A point worth emphasizing is that higher organisms are characterized not only by eukaryoticity, but also by multicellularity. This second feature evolved gradually from unicellular microorganisms. The prokaryotic blueprint, on the other hand, is a consequence of chemical evolution. On a geologic timescale prokaryogenesis is almost instantaneous. It follows from these considerations that multicellularity is also a consequence of chemical and biological evolution in a terrestrial-like environment.

We have not insisted on understanding of all the intermediate steps that led from organic chemistry to life (still an open problem). In the distribution of life in the universe, we do not insist on filling in all the biochemistry and molecular biology details that are involved in the transition from the world of single-celled eukaryotes to multicellular organisms, neurones, and brains.

2. Eukaryogenesis as a Factor in the Drake Equation

The strategy of not insisting on a full picture of all the intermediate stages of chemical and biological evolution has the advantage of allowing us to concentrate on the central problem of defining the science of the distribution of life in the universe. We maintain that the real problem of the presence of life in the universe is narrowed down to the problem of understanding eukaryogenesis itself. The Drake Equation may help us to drive the point home. The key parameter in the search for other civilizations is written as f_i , denoting the fraction of life-bearing planets, or satellites, where biological evolution produces an intelligent species. An early reference regarding the transition from prokaryotes to eukaryotes, in relation to the Drake Equation (Sagan 1973, p. 113), was made in the context

of the search for extraterrestrial intelligence (SETI). We consider the Drake Equation in Table 1.

Table 1. A simplified form of the Drake Equation.

$N = \kappa f_i,$	
N	the number of civilizations capable of interstellar communication
κ	a constant of proportionality involving several factors that we need not discuss here
$f_i,$	the fraction of life-bearing planets, or satellites, where biological evolution produces an intelligent species

We would like to underline that the Drake parameter f_i is itself subject to the equation explained in Table 2:

Table 2. A simplified form for the equation for the f_i parameter.

$f_i = k f_e,$	
$f_i,$	the fraction of life-bearing planets, or satellites, where biological evolution produces an intelligent species
k	a constant of proportionality involving several factors that we need not discuss here
f_e	the fraction of planets, or satellites, where eukaryogenesis occurs

Our conjecture motivates the search *within our own solar system* for a key factor (f_e) in the distribution of life in the universe, including intelligent life. The extrapolation of the transition to multicellularity into an extraterrestrial environment is suggested by the selective advantage we have already emphasized of organisms that go beyond the single-cell stage. Such organisms have the possibility of developing nervous systems and, eventually, brains, intelligence, and civilizations. If prokaryogenesis is possible on a short geological timescale, there are going to be evolutionary pressures on prokaryotes to evolve due to symbiosis, horizontal gene transfer, and natural selection.

In fact, these evolutionary mechanisms are going to provide strong selective advantage to those cells that can improve gene expression by compartmentalization of their genomes. (Larger genomes would be favored, since organisms with such a genetic endowment would have a better capacity for survival, and hence, a greater ability to pass their genes to their progeny.)

Whether the pathway to eukaryogenesis in a European-like environment, or elsewhere in the cosmos, has been followed, is clearly still an open question. We already know that f_e is non-vanishing on Earth. What is suggested in Table 2 is that, as well as searching for intelligence, the more restricted search for eukaryogenesis is sufficient for understanding one of the main aspects of SETI. What is being implicitly assumed is that trees of life, other than our own, are capable of producing intelligence.

3. Testing the Drake Equation in Our Solar System

As a guideline in our search for a way out of the impasse created by still not having had a first contact with an extraterrestrial civilization, we assume, as a working hypothesis, that the evolution of life in the universe can be explained only in terms of evolutionary forces that we experience today in our local environment: if other intelligence has developed on extrasolar planets, they must have gone through eukaryogenesis. More precisely we assume that:

Life is not only a natural consequence of the laws of physics and chemistry. Once the living process has started, then the cellular plans, or blueprints, are also of universal validity: The simplest cellular blueprint (prokaryotic) will lead to a more complex cellular blueprint (eukaryotic).

Eukaryogenesis will occur inexorably because of evolutionary pressures driven by environmental changes in planets, or satellites, where conditions may be similar to terrestrial ones.

Although there are still many questions to be answered, at present it seems possible (although not an easy matter) to penetrate the oceans of the icy Galilean satellites, provided it is confirmed that there are submerged oceans of liquid water. We can conceive experiments addressed specifically to the question of the search for extraterrestrial eukaryotes, although clearly many such experiments could be formulated (Chela-Flores 1998b). To sum up, verifying that f_e (cf., Table 2) is non-vanishing in one of the Galilean satellites goes a long way towards making contact with the initial steps towards other intelligence. It also would lay the foundation for the theory of the distribution of life in the universe.

Everyone agrees that the Newton's theory of gravitation can be extrapolated without any difficulty throughout the universe, except for the minor corrections implied by the theory of general relativity. One example has already been discussed regarding the orbits of Jupiter-like planets. The case for extrapolating the theory of biological evolution throughout the cosmos, however, requires more care and is still an open problem. Arguments against the hypothesis of "biogeocentrism" (the view that maintains that life is confined to planet Earth) can now be formulated thanks to progress in our understanding of Darwinian evolution. The role of randomness has been qualified since Darwin's time. The role of chance is implicit in *The Origin of Species*. This aspect of Darwinism was captured by Monod in his book *Chance and Necessity*: this was expressed with the suggestive contrast between chance mutations and the necessary filtering of natural selection (Monod 1972, p. 136). We have also seen that molecular biology constrains chance (De Duve 1995, p. 160). Evolutionary convergence will be an additional factor to take into account, as discussed in detail recently (Conway-Morris 1998, p. 9). To sum up, Darwinian contingency is constrained and evolution tends to converge on similar solutions when natural selection acts on similar organic materials that are in similar environments.

On the other hand, cosmochemistry and planetary science present us with a picture in which the environments where life can originate are limited. We already are gathering information on a significant number of Jupiter-like planets around stars in our cosmic neighborhood. Such planets arise from subnebulae that are likely to yield an array of satellites around them. In our outer solar system this can be confirmed. Each of the giant planets has a large suite of satellites.

Evidence is leaning in favor of the existence of Jovian planets with masses larger than Jupiter; hence, tidal heating responsible for Io's volcanic eruptions could be even more efficient in other solar systems. On Europa it is not completely clear that tidal heating may produce hydrothermal vents capable of giving rise to life; tidal heating may be even more efficient on satellites orbiting around Jupiter-like planets with masses larger than the Jovian mass. Natural selection will be working on a finite number of similar environments.

Darwinism cannot be seen simply as a dichotomy between chance and necessity, but constrained chance and convergent evolution will favor analogous pathways that have led to intelligence on Earth. For these reasons we have advocated a dual approach to the problem of the distribution of life in the universe: one approach is at the cellular level in our solar system, in other words, the search for extraterrestrial eukaryotes. The other approach is the time-honored SETI approach at the multicellular level in other solar systems.

4. Is There Liquid Water on Europa?

In 1976 the Voyager missions provided low-resolution images of the surface of Europa. They showed a number of intersecting ridges and *linae* (cracks on the surface). Besides, we learnt that craters were not abundant, suggesting that Europa has been geologically active until a relatively recent date (or, alternatively, there may have been "resurfacing" from liquid water from below).

The Galileo mission has added much to these early insights. One example is some form of "ice-tectonics". The Jet Propulsion Laboratory, which is handling the mission for NASA, has released some images which suggest that part of the surface is understood in terms of shifting plates of ice. From all the information gathered from Voyager and Galileo, reasonable guesses have been put forward, in the sense that there may be a substantial amount of liquid water between the silicate crust and the icy surface. The trigger for the melting of the ice that we "see" spectroscopically from Earth could be tidal heating.

Some of the evidence for liquid water may be inferred from the linear features on the surface of this satellite. One particular case is provided by triple bands. Each structure consists of two dark bands separated by a bright intermediate ridge. These fractures on the icy surface, which may be the result of tidal deformation, are subsequently filled in with water and silicates from Europa's interior. After water and minerals are separated on the surface, freezing would result in water expansion to form the central ridge. We may conclude that the possible presence of liquid water in Europa forces upon us the question of the possible presence of European life, as we have done here. Galileo images have reinforced, but not yet proved, the existence of a European ocean.

Speculating on the putative European biotope is not an idle exercise, for technology has reached a point at which funding seems to be the only barrier preventing us from a concentrated campaign of exploration of the putative ocean. We have argued, on the basis of the Galileo images, that many hints already exist to suggest that part of the ice covering the silicate core is liquid water that forms an ocean or lakes analogous to those found in Antarctica. The same images allow us to go further: resurfacing of a large proportion of the European surface is a fact, since its craters are few in number. The remarkable ones that do

exist provide further hints of its liquid-water interior. But resurfacing also hints at submerged geologic activity. Europan volcanism may resemble terrestrial volcanism (this follows from the analogous formation of the terrestrial planets and the satellites of the Jovian planets). Earth-like geologic activity includes a candidate for the origin of life as we know it, namely, hydrothermal vents. It is clear that the chemical disequilibrium arising from thermal gradients present in the water circulating through the hot volcanic rock could drive chemical reactions that lead to life (Jakosky 1998, p. 223). The remaining question is whether an ample supply of organics could be found on the seafloor. In fact, the carbon abundance of Europa should be correlated with solar abundance. This is further supported by evidence supplied by carbonaceous chondrites.

5. Can Life Begin in the Absence of Starlight?

The answer to this question is important for the possible existence of life on Europa. The question may even be more relevant for any of the other icy satellites of the outer solar system and elsewhere in the galaxy, either on satellites of Jupiter-like systems, or even on planets in interstellar space, if these bodies exist (Stevenson 1999).

Earth-bound eukaryotes depend on an oxygenic atmosphere, which was in turn produced by prokaryotic photosynthesis over billions of years. A possible scenario favoring the existence of Europan microorganisms seems to decouple hydrothermal-vent systems from surface photosynthesis. Indeed, experiments have already shown that chemical evolution leading to biological evolution is possible in conditions similar to those of hydrothermal vents (Huber & Wächtershäuser 1998; Imai *et al.* 1999). Further, the delivery of amino acids at hydrothermal vents is possible, either by cometary or by meteoritic delivery (Chyba 1998). Rather than prebiotic evolution, the genesis of a *primitive cell* in the deep ocean, independent of photosynthesis, is still a wider issue to be settled experimentally. The possibilities of primary deep-sea or, alternatively, deep-underground evolution, are at present open questions. To clarify this point we may recall some related evidence against hydrogen-based microbial ecosystems in basalt aquifers, namely ecosystems in rock formations containing water in recoverable quantities (Anderson *et al.* 1998). This experiment raises doubts about the specific mechanism proposed for life existing deep underground (Stevens & McKinley 1995).

What remains to be shown in microbiology is that some barophilic and thermophilic microorganism has a metabolism that can proceed in completely anoxic conditions, deprived of carbon and organic-nitrogen derived from surface photosynthesis. For example, such experiments probing the ability of a given microorganism to survive in well-defined environments were performed when it was shown that *Cyanidium*, a primitive alga, was able to thrive in a pure carbon-dioxide atmosphere (Seckbach *et al.* 1970). Thus, the case for life's origins, either through chemosynthesis first, or through a secondary reliance on photosynthesis at hydrothermal vents (by using oxygen dissolved in the seawater), or deep underground, are still open questions.

A possible source material for a Europan microfauna, at hydrothermal systems, can be understood in terms of the delivery of carbonaceous chondrites.

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These small objects of the solar system have a substantial proportion of carbon, including hydrocarbons. For instance, the Murchison meteorite has over 50 ppm of hydrocarbon. Material of this kind, under pressure and heat at some depth, would ooze out its hydrocarbon fraction, which would subsequently reach the surface by buoyancy forces. The reason for this phenomenon is that these fluids are less dense than the rocks. This is a point made earlier (Gold 1997). As an example, consider the Guaymas Basin in the Gulf of California. It has a hydrothermal field which is the locus of rapid formation of petroleum hydrocarbons from organic matter by the action of hydrothermal fluids (Lutz & Kennish 1993). This field represents a typical example of an important source of carbon for microbiota, which constitutes the support a rich macrofaunal community.

An important point was made recently by Ken Nealson and his colleagues (Gaidos *et al.* 1999). I will argue that their comments, which are apparently restricted to the possible occurrence of prokaryogenesis on a Galilean satellite does, in fact, imply the possibility that eukaryogenesis as well could have occurred in a European ocean. Even in the case when oxidants are scarce, the presence of oxidized metals, such as ferric iron, may provide at low-temperature the possibility of reduction by, for instance, hydrogen sulphide, especially under low pH. This process is thermodynamically favorable. Such reactions might support a simple ecology in a Europa-like environment within hydrothermal vents. Counterparts of such communities are known on Earth—we are aware of the existence of mineral-reducing bacteria. On the other hand, hydrocarbons leaking from the seafloor provide a source of chemical energy that nourishes creatures similar to hydrothermal-vent fauna. Such prokaryotes are subject to evolutionary pressures.

There are no refuges against evolution on Earth (Chela-Flores 1997; Little *et al.* 1998). Even fossils from Silurian hydrothermal-vent fauna demonstrate that there has been extinction of species on these locations, which at first sight seem to be far removed from evolutionary forces. For this reason even the presence of conditions favorable to extremophiles only, such as the microbiota pointed out above, is sufficient reason to enquire if over geologic time, in the absence of refuges against evolution, the prokaryotic blueprint has bloomed into full eukaryogenesis.

While this situation remains unsettled, the space agencies must make plans for experiments that will use the technological capability tested in the Antarctic to deliver equipment underneath the crust of icy satellites such as Europa and Callisto. The search for prokaryogenesis in the solar system should not be its primary goal. On the contrary, testing for the presence of the eukaryotic blueprint right from the beginning of the *in situ* exploration of the Galilean satellites seems preferable. To conclude, one of the main thrusts of solar system exploration should be focused on the biomarkers of the eukaryotic stage of development.

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