

United Nations Educational Scientific and Cultural Organization
and
International Atomic Energy Agency
THE ABDUS SALAM INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS

TESTING THE DRAKE EQUATION IN THE SOLAR SYSTEM¹

Julian Chela-Flores
*Instituto de Estudios Avanzados, (Universidad Simon Bolivar),
Apartado 17606 Parque Central, Caracas 1015A, Venezuela
and
The Abdus Salam International Centre for Theoretical Physics, Trieste, Italy.*

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: $f_i = k f_e$. 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 in 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.

MIRAMARE – TRIESTE

September 1999

¹To be published in the Proceedings of *Astronomical Society of the Pacific Conference Series (2000)*.

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 emphasise 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-honoured sub disciplines 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 lack 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 Man (Chela-Flores 1998a-c). Once eukaryogenesis took place on Earth the steps leading up to multicellularity were inevitable, namely, cell signalling and the organisation into co-operative 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 three 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 favoured the formation of tissues of primitive multicellular organisms. A point worth emphasising is that higher organisms are not only characterised by eukaryoticity, but also by multicellularity. This second feature

Table 1: A simplified form of the Drake Equation.

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

evolved gradually from unicellular microorganisms. The prokaryotic blueprint, on the other hand, is a consequence of chemical evolution. In a geologic time scale 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 either in 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 civilisations 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 with the Drake Equation (Sagan 1973), was made in the context of the search for extraterrestrial intelligence (SETI). We consider the Drake Equation in Table 1.

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

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 emphasised of organisms that go beyond the single-cell stage. Such organisms have the possibility of developing nervous systems and, eventually, brains, intelligence and civilisations. If prokaryogenesis is possible in a short geological time scale, there are going to be

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

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

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 compartmentalisation of their genomes. (Larger genomes would be favoured, since organisms with such genetic endowment would have better capacity for survival, and hence better 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 guiding line in our search for a way out of the impasse created by still not having had a first contact with an extraterrestrial civilisation, we assume, as a working hypothesis, that 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, but 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 the 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 iced galilean satellites, provided it is confirmed that there are submerged oceans of liquid water. We can conceive experiments ad-

dressed 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 for 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 in the theory of general relativity. One example has already been discussed regarding the orbits of Jupiter-like planets. Secondly, the case for extrapolating the theory of biological evolution throughout the cosmos 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). We have also seen that molecular biology constrains chance (De Duve 1995). Evolutionary convergence will be an additional factor to take into account, as discussed in detail recently (Conway-Morris 1998). 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 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 neighbourhood. 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 favour 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 favour 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-honoured SETI approach at the multicellular level in other solar systems.

4 Is There Liquid Water in Europa?

In 1976 the Voyager missions provided low resolution images of the surface of Europa. They showed a number of intersecting ridges and lineae (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 the early insights we already had. 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 iced surface. The trigger for the melting of the ice that we ‘see’ spectroscopically from the 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 iced surface may be the result of tidal deformation, which subsequently are filled in with water and silicates from its 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, forming 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. European 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). The remaining question is whether an ample supply of organics could be found in the seafloor of the ocean. 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 iced 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 favouring the existence of European 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 and Wachtershauser 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 in the future. 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 on the specific mechanism proposed for life existing deep underground (Stevens and 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 from 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 sea-water), or deep underground, are still open questions.

A possible source material for a European microfauna, at hydrothermal systems, can be understood in terms of the delivery of carbonaceous chondrites. 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 et al. 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 in a Galilean satellite does, in fact, imply the possibility that eukaryogenesis could have occurred in a European ocean as well. Even in the case when oxidants are scarce, the presence of oxidised 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 favourable. Such reactions might support a simple ecology in a European-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 favourable 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, plans for experiments have to be made by the space agencies, as the technological capability tested in the Antarctic is consolidated for delivering equipment underneath the crust of the iced satellites, such as Europa and Callisto.

We have argued that the search for prokaryogenesis in solar system exploration should not be its primary goal. The issue is so large. In fact, it is the largest issue since Darwin's time, and consequently should not be treated lightly. On the contrary, testing for the presence of the eukaryotic blueprint seems preferable, right from the beginning of the *in situ* exploration of the galilean satellites. To conclude, we have argued that one of the main thrusts of solar system exploration should be focused on the biomarkers of the eukaryotic stage of development.

References

- [1] Anderson, R.T., Chapelle, F.H. & Lovly, D.R. 1998, *Science*, 281, 976
- [2] Brocks, J.J., Logan, G.A., Buick, R.B. & Summons, R.E. 1999, *Science*, 285, 1033
- [3] Chela-Flores, J. 1997, *Instruments, Methods and Missions for Investigation of Extraterrestrial Microorganisms* (Hoover, R.B. Ed.), Proc. SPIE, 3111, 262
- [4] Chela-Flores, J. 1998a, *Origins Life Evol. Biosphere*, 28, 215
- [5] Chela-Flores, J. 1998b, *Origins Life Evol. Biosphere*, 28, 583

- [6] Chela-Flores, J. 1998c, *The Phenomenon of the Eukaryotic Cell*. In: Evolutionary and Molecular Biology: Scientific Perspectives on Divine Action. Robert John Russell, William R. Stoeger & Francisco J. Ayala, Editors. Vatican City State/Berkeley, California: Vatican Observatory and the Center for Theology and the Natural Sciences, 1998. pp. 79-99
- [7] Chyba, C. 1998, *Nature*, 395, 329
- [8] Conway-Morris, S. 1998, *The Curcible of Creation. The Burgess Shale and the Rise of Animals* Oxford University Press, New York. pp. 9-14
- [9] De Duve, C. 1995, *Vital dust: Life as a Cosmic Imperative*. Basic Books: New York. pp. 160-168
- [10] Gaidos, E.J. Nealson, K.H. & Kirschvink 1999, *Science*, 284, 1631
- [11] Gold, T. 1997, Reasons for expecting subsurface life on many planetary bodies. In: Instruments, Methods and Missions for Investigation of Extraterrestrial Microorganisms, (Hoover, R.B. Ed.), Proc. SPIE, 3111, 7
- [12] Huber, C. & Wachtershauser, G. 1998, *Science*, 281, 670
- [13] Imai, E., Honda, H., Hatori, K, Brack, A. & Matsuno, K. 1999, *Science*, 283, 831
- [14] Jakosky, B. 1998, *The Search for Life in Other Planets*. Cambridge University Press. p. 223
- [15] Little, C.T.S., Herrington, R.J., Maslennikov, V.V. & Zaykov, V.V. 1998, The fossil record of hydrothermal vent communities. In: Mills, R.A. & Harrison, K. (eds.) *Modern Ocean Floor Processes and the Geologic Record*. Geological Society. London, Special Publications, 148, 259
- [16] Lutz, R.A. & Kennish, M. J. 1993, *Rev. Geophysics* 31, 211
- [17] Monod, J. 1972, *Chance and Necessity*. Collins: London. p. 136
- [18] Sagan, C. 1973, in: *Communication with Extraterrestrial Intelligence (CETI)*. The MIT Press: Cambridge, Massachusetts. p. 113
- [19] Seckbach, J., Baker, F.A. & Shugarman, P. M. 1970, *Nature*, 227, 744
- [20] Stevens, T. O. & McKinley, J. P. 1995, *Science*, 270, 450
- [21] Stevenson, D. J. 1999, *Nature*, 400, 32