Seckbach, J. and Chela-Flores, J. (2010). Astrobiology: From extremophiles in the Solar System to extraterrestrial civilizations, to be published in "Life on Earth and other Planets, accepted for publication, Springer, and
Proceedings of the Budapest Conference, August 2009.

JOSEPH SECKBACH[1] and JULIAN CHELA-FLORES[2]

ASTROBIOLOGY: FROM EXTREMOPHILES IN THE SOLAR SYSTEM TO EXTRATERRESTRIAL CIVILIZATIONS

Abstract. Life on Earth is ubiquitous. Most of the organisms that we know thrive in normal environments that we consider to be ambient habitats. Extremophiles are among the microorganisms living on the edge of life under severe conditions. In recent years microorganisms have been discovered living in extreme environments, such as very high temperature (up to 115^0 C), and also at very low temperature (~ minus 20^0 C). In addition, they can also withstand a variety of stresses, amongst them we mention both ends of the pH range; very strong acidity vs. high alkalinity; saturated salt solutions and high hydrostatic pressure. Astrobiology considers the possibility that extraterrestrial civilizations may be present in some exoplanets in the large suite that has been discovered so far. The instruments of research are radio telescopes. Astrobiology also raises the possibility of life elsewhere in the Solar System. (The most promising examples are Mars, Europa, and possibly Titan and Enceladus). We suggest that if microbial communities can thrive under extreme conditions on Earth, they could also emerge on extraterrestrial environments.

1. Introduction

We know that life exists on Earth in almost every ecological niche. One of the prerequisites for life is the availability of liquid water, sources of energy and a reasonable supply of organic molecules. From our experience with the Earth biota, wherever there is water, there is a good opportunity of finding living organisms.

The search for extraterrestrial life is encouraged by a comparison between organisms living in severe environmental conditions on Earth and the physical and chemical conditions that exist on some Solar System bodies. The extremophiles that could tolerate more that one factor of harsh conditions are called poly-extremophiles. There are unicellular and even multicellular organisms that are classified as hyperthermophiles (heat lovers), psychrophiles (cold lovers), halophiles (salt lovers), barophiles (living under high pressures), acidophiles (living in media of the lower scale of pH). At the other end of the pH scale they are called alkaliphiles (namely, microbes that live at the higher range of the pH scale). Thermo-acidophilic microbes thrive in elevated thermo-environments with acidic levels that exist ubiquitously in hot acidic springs.

Cyanidium caldarium, is a classical example of an acido-thermophilic red alga that thrives in places such as hot-springs (<57^0 and in the range 0.2-4 pH). This algal group shows a higher growth rate (expressed as number of cells and higher oxygen production when cultured with a stream of pure CO_2, rather than when bubbled with a stream of air (Seckbach, 2010). It has been reported that *Cyanidium* cells resisted being submerged in sulfuric acid (1N H_2SO_4). This is a practical method for purifying cultures in the laboratory and eliminating other microbial contamination (Allen, 1959). The psychrophiles thrive in cold environments, such as within the territories found in the Siberian permafrost, around the North Pole in Arctic soils, and they may also grow in Antarctica.

Barophilic microorganisms can tolerate a pressure of 1000 atmospheres on the seafloor, while other barophilic microorganisms have been detected in the subsurface of dry land. In hypersaline areas (such as the Dead Sea, Israel) we find halophilic bacteria (Arahal *et al.,* 1999) and algae that can balance the osmotic pressure of hypotonic external solutions (Oren, 1988).

Chroococcidiopsis is one of the most primitive cyanobacterium known so far. This microbe survives in a wide range of extreme habitats that are hostile to most other forms of life. *Chroococcidiopsis* grows in hot springs, in hypersaline habitats, in a number of hot, arid deserts throughout the world, as well as in the frigid Ross Desert in Antarctica (Fewer *et al*., 2002).

Recently, the segmented microscopic animals tardigrades, (0.1 – 1.5 mm) have been under investigations (Goldstein and Blaxter, 2002; Horikawa, 2008). These "water bears" are polyextremophilic, and are able to tolerate a temperature range from about 0^0C up to + 151^0C (much more that other known microbial prokaryotic extremophiles, Bertolani *et al.,* 2004). But even low Earth orbit extreme temperatures are possible: tardigrades can survive being heated for a few minutes to 151°C, or being chilled for days at -200°C, or for a few minutes at -272°C, 1° warmer than absolute zero (Jönsson *et al.,* 2008). These extraordinary temperatures were discovered by an ESA project of research into the fundamental physiology of the tardigrade, named TARDIS. Tardigrades are also known to resist high radiation, vacuum, and anhydrous condition for a decade in a dehydrated stage and can tolerate a pressure of up to 6,000 atmospheres. These aquatic creatures are ideal candidates for extraterrestrial life and for withstanding long periods in space. They have already been used in space and have survived such stress.

For further information see in Google the images of this animal (http://en.wikipedia.org/wiki/Tardigrade), and in Tardigrade - New World Encyclopedia (http://www.newworldencyclopedia.org/entry/Tardigrada).

Several chapters dealing with relevant topics as this paper have been published in the *Cellular Origin, Life in Extreme Habitats and Astrobiology* series www.springer.com/series/5775

2. Some microbes may be dormant for long periods in harsh conditions

Some microorganisms live in desiccation conditions (in dormant stage and at minimum metabolic rates). In such circumstances, these microbes, or their spores, could last in a dormant stage for millions of years before being revived. Recently, researchers have breathed new life into bacteria trapped deep under glacial ice in Greenland for over 120,000 years. In addition, scientists found an ancient ecosystem below the "Blood Falls" in an Antarctic glacier (Mikucki and Priscu, 2007; Mikucki, *et al.,* 2009). It was determined that this community had survived millions of years in a salty pool without light or oxygen. J. Grom (2009) decribes the phenomenon as follows:

> "Scientists have found life in an ecosystem trapped underneath a glacier in Antarctica for nearly 2 million years. The microbes, they suggest, are surviving the dark, oxygen-free waters by drawing energy from sulfur and iron. The findings provide insight into how life may have survived "Snowball Earth"—periods when some scientists speculate that the planet was entombed in ice—and hint at the possibility of life in other inhospitable environments, such as Mars and Jupiter's icy moon Europa."

Among the biological samples, there was a diversity of bacteria that thrive in cold, salty water loaded with iron and sulfur. The water averages minus 10^0C (the high salt concentration prevents the water from freezing). These bacterial cells convert iron and sulfur into their nourishment (chemosynthesis). The fact that life can thrive in one of the most extreme environments on Earth, supports the hypothesis that it has emerged in extraterrestrial ecosystems as well. R. Cano and M. Borucki (1995) reported the revival and identification of bacterial spores within the intact body of a bee that was trapped in amber for 25 to 40 million years. R. H. Vreeland *et al.* (2000) have claimed to reawaken bacteria from spores inside a 250 million-year-old salt crystal. There has been some controversy regarding these ancient extant bacteria (Nickle *et al.,* 2002; Oard, 2001), or whether they may represent the most ancient life forms on Earth (Hoyle, 2001). Other authors await confirmation of the Vreeland *et al.* results in different salt deposits (Adam, 2000).

3. Astrobiology

Does life exist beyond our planet and, if so, is it comparable to what we know here on Earth? These are some of the most fascinating questions facing science today, particularly astrobiology, the study of the origin, evolution, distribution and destiny of life in the universe. Three strategies have been devised for the search for extraterrestrial life: firstly, the study of the cellular makeup of exotic organisms on Earth; secondly, the search for organic matter and living micro-organisms beyond Earth; and last but not least, the use of radio telescopes to detect signals of intelligent behavior in the universe. The first strategy has focused on understanding how life began on Earth. Research has shown exotic organisms living in inhospitable environments, such as the seafloor, the Antarctic glacial sheets and volcanic lava streams—all of which display temperatures and pressures that may have been present during the process of the Earth's evolution. Perhaps one of the most unexpected recent discoveries has been that there are underground ecosystems, which to a large extent are independent of sunlight, extending our old concept of what was a habitable zone in a given solar system. Research into our own origins not only broadens our appreciation of the ability of extremophiles to conquer every accessible niche (cf., Part 1), but such investigation also helps us understand the environmental extremes tolerated by simple organisms.

The second strategy for deciding if we are not alone in the universe is a search for the simplest forms of organic matter—amino acids or proteins—that may be embedded in ancient rocks of planets, comets or meteorites, or even suspended in interstellar clouds. The search has focused elsewhere in the Solar System: Mars, Europa (a moon of Jupiter), and Titan and Enceladus (satellites of Saturn). The discovery of meteorites from Mars suggests that all the terrestrial planets (Mercury, Venus, the Earth, the Moon and Mars) at one stage in the past may have been in biological intercourse. There is compelling evidence that liquid water has flowed in the geologically recent past on Mars (or may even be flowing now).

The third strategy used in the search of life beyond Earth is the most relevant one to the subject matter of the present book. It relies on radio telescopes such as the huge one at the National Astronomy and Ionosphere Center in Arecibo, USA. These 'dishes' actually have two roles to play: first and foremost, they help to examine wavelengths that cannot be seen by the human eye; for example, radio waves and microwaves. Such information has proven to be essential for understanding the movement and behavior of planets and stars. Secondly, radio telescopes also seek anomalies in microwaves and radio waves wafting across the universe. Such anomalies may represent the imprint of intelligent life. Thus far astronomers have been scanning the radio and microwave spectrum for almost half a century with no reliable signal yet from an extraterrestrial civilization. But this initial difficulty does not imply that the initiative is likely to be abandoned (Ekers *et al.,* 2002).

4. Is extraterrestrial life a possibility that can be tested?

Data and photographs transmitted by the Voyagers revealed previously unknown details about each of the giant planets and their moons. Close-up images from the spacecraft uncovered a variety of phenomena in the Jupiter system: most surprising amongst them is the volcanic activity on Io, one of its so-called galilean satellites. Amongst the Voyager discoveries one of the most significant was the icy surface of the Jovian satellite Europa. The excitement surrounding Europa is due to the subsequent Galileo mission (1995-2003). This mission has changed the way we look at the Solar System and especially Europa (and even to the possibility of exo-moons that may be inhabitable). This mission was the first to conduct long-term observations of the Jovian system from orbit. It found evidence of subsurface saltwater on Europa, Ganymede and

Callisto and further revealed the intensity of volcanic activity on Io. From the similarity of the processes that gave rise to planets and satellites, we may expect that hot springs may lie at the bottom of the ocean triggered by tidal stresses and radiogenic energy.

It has been assumed in the past that Jupiter's proto-nebula must have contained many organic compounds. Organisms similar to thermophiles could possibly exist at the bottom of Europa’s ocean. However, given the incomplete understanding of the evolution of early life on Earth, at present we should allow for the possibility that microorganisms are a possible Europan biota (cf., Sec. 4.2). We may add that up to the present time we do not fully understand the evolution of the earliest ancestor of all life on Earth. Indeed, plate tectonics has obliterated fossils of the early organisms from the crust of the Earth, which would constitute the only record of the evolution of early life.

Testing whether life is extant on the icy satellites of the Outer Solar System depends on the choice of the right instrumentation. The British Penetrator Consortium is developing an attractive possibility. Penetrators are being developed for preliminary trials on our own Moon. The MoonLITE mission is a proposed, UK-led lunar science mission comprising 4 scientific penetrators that will make *in-situ* measurements at widely separated locations on the Moon with a suite of scientific instruments that will perform a variety of measurements on the lunar surface. There is a related proposal for ESA, under the name of LunarEX (Smith *et al.,* 2008), consisting of small projectiles that can be delivered at high velocity to reach just beneath the surface of satellites for probing samples of surficial chemical elements. They are appropriate for *in-situ* chemical laboratories. Eventually, these instruments could be tested on the icy surface of Europa and Ganymede in our next visit to the Jovian System (cf., Sec. 4.2).

4.1 MARS

The present view on the surface of Mars shows that Mars in the past was wet and warmer than today. There photos show several contours of water bodies carved in the surface, such as tunnels, deep rivers, lakes, canyons, and other structures where water used to run. Therefore, our nearest-neighbor planet is a candidate for having supported life in the past. We cannot exclude its presence in some isolated environments. The possibility of extending the biosphere deep into the silicate crust in another terrestrial planet deserves special attention. The emergence of life on Mars is pertinent to astrobiology, since we cannot exclude the analogy with organisms that have been found to inhabit deep in the silicate crust of the Earth. Such microbes may have been deposited with the original sediment. Life, in these conditions may have evolved during an early 'clement period' that may have occurred contemporary with our own Early Archean: the Noachian Epoch, or Early Hesperian in Mars stratigraphy, according to the standard terminology (Sleep*,* 1994). Possible candidates for sites in which life may have evolved are located in the Tharsis region located on Mars' equator, at the western end of Valles Marineris, where volcanic activity has taken place since, by analogy with the Earth, the heat from underground magma may have produced hot springs, which are known to be possible sources of hyperthermophilic microorganisms (cf., Parts 1 and 2). Knowledge of these possible locations raises the question whether life may have survived till the present confined to regions where pockets of liquid water may occur.

In the short term the Mars missions that are being planned now will add valuable insights as to the possibility of extant, or extinct life on Mars. For instance, the Mars Science Laboratory (MSL), a NASA rover is expected to be launched in 2011. The MSL rover will include instruments for the analysis of soil samples. It will also investigate the past or present ability of Mars to support microbial life. On the other hand, ExoMars (Exobiology in Mars) is planned for 2018. This will be collaboration between ESA and NASA. A robotic rover will be sent to the surface of Mars. It will deploy a rover carrying analytical instruments dedicated astrobiology and geology. The ExoMars spacecraft will consist of an orbiter, the carrier module. The rover itself will carry a scientific payload. One of its aims is to search for possible biosignatures of Martian life, past or present. Especially significant will be the European orbiter, whose aim includes tracking down sources of methane that have been detected in the past (Lefèvre and

Forget, 2009). Confirming the presence of methane is a high priority; nevertheless, an abiogenic origin is thought to be equally plausible (Atreya *et al.*, 2007).

4.2 EUROPA

The Galileo Space Mission (1995-2003) has provided ample evidence for an ocean on Europa underneath its frozen icy surface. One of the primary goals of astrobiology is to determine whether life ever existed in places other than the Earth and, if so, what were the environmental conditions that made it possible. The discovery of an independent life form, a separate tree of life from our own on Europa, would not only be fascinating in its own right, but it would shed revealing light on the microbes that inhabited the Earth more than four billion years ago, when higher temperatures were common and the continual bombardment of meteorites and comets made the surface of the Earth a hostile environment.

From the point of view of the possibility of the existence of life on Europa, we should consider a lake called Vostok (**Karl e***t al.,* 1999), which is the largest of about 80 subglacial lakes in Antarctica. Its surface is of approximately 14,000 km^2 and its volume is 1,800 km^3. Indeed this Ontario-sized lake in Eastern Antarctica is also deep, with a maximum depth of 670 m. On the other hand, from the point of view of microbiology, the habitat-analogue provided by Lake Vostok for the Europa environment seems appropriate. Lake Vostok appears to be harboring hydrothermal vents beneath the water surface. This is suggestive of what may be occurring on Europa. The circulation of pure water in Lake Vostok will be driven by the differences between the density of meltwater and lake water. Geothermal heating will warm the bottom water to a temperature higher than that of the upper layers.

The water density will decrease with increasing temperature resulting in an unstable water column. This leads to vertical convective circulation in the lake, in which cold meltwater sinks down the water column and water warmed by geothermal heat ascends up the water column (Siegert *et al.*, 2001). Similarly, Europa may also have geothermally-heated warm water under its ice-crust. Processes of the type that occur in Lake Vostok may be taking place on Europa, where biogenic sulfur may be reaching the surface (Singer *et al.,* 2003).

Early discussions considered the possibility exploring Europa's habitability in terms of direct use of a submersible called a hydrobot (Horvath *et al.,* 1997). This question is still relevant a decade later, in terms of new NASA tests of an autonomous underwater vehicle (AUV) called ENDURANCE for the Astrobiology Science and Technology for Exploring Planets (ASTEP) program (Doran *et al.,* 2007), a worthy successor of our cryobot-hydrobot early planning.

In relation with the distribution and destiny of life in the universe we have argued that if the experiments on evolution were to be successful, the science of the distribution of life in the universe would lie on solid scientific bases, for instance, direct verification of whether the transition prokaryote-eukaryote has taken place within the Solar System bodies (Chela-Flores, 1998, 2000).

Beyond Galileo a return to the Jupiter System is being considered in the next decade with the Europa Jupiter System Mission (EJSM), a worldwide collaboration that will point mainly on Europa and Ganymede, the largest satellite in the Solar System. The mission consists of two flight elements operating in the Jovian system: the NASA-led Jupiter Europa Orbiter (JEO), and the ESA-led Jupiter Ganymede Orbiter (JGO). JEO and JGO will explore Europa and Ganymede, respectively (Grassett *et al.,* 2009). Possible biomarkers accessible to EJSM have been discussed recently (Chela-Flores and Kumar, 2008).

4.3 IS HABITABILITY POSSIBLE ELSEWHERE?

Titan is a potential cradle for life. After the early successes of the Cassini-Huygens Mission, many interesting questions have been raised, including the source of methane, and possible ammonia-water ocean, inside this large satellite that resembles the Archaean Earth in some respects. For instance, Titan has a nitrogen atmosphere, and so does the Earth, including its atmosphere before life. Titan has organics that are almost certainly supplied in the absence of life. Not all the Earth's prebiotic ingredients are present on Titan though, because the Earth probably had CO_2 unlike Titan (Coustenis and Taylor, 2008).

Other reasons for focusing on Enceladus is that Cassini flew within 175 km in 2005 confirming the presence of an atmosphere: their instruments found that the atmosphere contains water vapor comprising up to about 65 percent, with molecular hydrogen at about 20 percent. The rest is mostly carbon dioxide and some combination of molecular nitrogen and carbon monoxide. Another Cassini instrument showed that the south pole is warmer than near the equator. The poles should be colder because the Sun shines so obliquely there. However, in small areas of the pole, concentrated near the fractures known as the "tiger stripes", the temperatures can reach temperatures of well under -110 K (-261 F). This should be compared with the equatorial temperature of approximately 80 K.

Cassini has also confirmed that icy jets shooting up to 500 km are ejected from Enceladus, a tiny satellite of Saturn. The presence of liquid water in its interior raises this moon to a prime candidate for the search for life. Saturn's moon Enceladus emits plumes of water vapour and ice particles from fractures near its south pole, suggesting the possibility of a subsurface ocean. The water plumes could be caused by a liquid ocean many kilometres underground, rather than by geysers erupting from a salty ocean just beneath the moon's surface (Postberg *et al.,* 2009).

5. Conclusions

All the above facts serve to encourage us to intensify our search for life on Earth's closest neighbors (terrestrial planets and satellites in the Outer Solar System). Further investigations, and especially the forthcoming missions to Europa and the various missions to Mars, will shed additional light on the potential extraterrestrial life on or inside Mars and Europa. A central role would be played by appropriately chosen instrumentation and we have described the high hopes that penetrators promise to yield in our search for life in Solar System exploration. We conclude that if life can thrive in some of the most extreme environments on earth, perhaps it can meet the challenges of existing elsewhere in the Solar System, including a europan biota under its icy surface sustained by chemosynthesis on hydrothermal vents at the seafloor.

6. Acknowledgment

The senior author (JS) thanks the Israeli and Hungarian Academies of Sciences and Humanities for their kindly support towards and during the conference of Astronomy and Civilization in Budapest (Aug. 2009).

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KEY WORDS:

Antarctica, Lake Vostok, Astrobiology, Cyanidium caldarium, eukaryotes and prokaryotes, Europa's ocean, Ganymede and Callisto, extraterrestrial life, extremophiles (hyperthermophile; psychrophiles, barophiles, galilean moons of Jupiter , life as we know it (or as we do not know it), life's iniquitousness on Earth, Mars, models for life elsewhere, tardigrade.

Address of authors:

[1]Hebrew University of Jerusalem (E-mail: seckbach@huji.ac.il) and

[2]The Abdus Salam ICTP, Strada Costiera 11; 34151 Trieste, Italy, and Instituto de Estudios Avanzados, IDEA, Caracas 1015A, República Bolivariana de Venezuela(E-mail: chelaf@ictp.it)