

Testing the universality of biology: a review

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Abstract: We discuss whether it is possible to test the universality of biology, a quest that is of paramount relevance for one of its most recent branches, namely astrobiology. We review this topic in terms of the relative roles played on the Earth biota by contingency and evolutionary convergence. Following the seminal contribution of Darwin, it is reasonable to assume that all forms of life known to us so far are not only terrestrial, but are descendants of a common ancestor that evolved on this planet at the end of a process of chemical evolution. We also raise the related question of whether the molecular events that were precursors to the origin of life on Earth are bound to occur elsewhere in the Universe, wherever the environmental conditions are similar to the terrestrial ones. We refer to ‘cosmic convergence’ as the possible occurrence elsewhere in the Universe of Earth-like environmental conditions. We argue that cosmic convergence is already suggested by observational data. The set of hypotheses for addressing the question of the universality of biology can be tested by future experiments that are feasible with current technology. We focus on landing on Europa and the broader implications of selecting the specific example of the right landing location. We have previously discussed the corresponding miniaturized equipment that is already in existence. The significance of these crucial points needs to be put into a wider scientific perspective, which is one of the main objectives of this review.

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The relative roles of contingency and convergence in evolution

‘What would be conserved if the tape of evolution were played twice?’ is a question that is relevant for astrobiology. It has been raised repeatedly in the past (Gould 1989; Fontana & Buss 1994). This question is not only relevant for understanding the proper role played by contingency in the evolution of life on Earth, but more significantly the replaying of the tape is a metaphor that underlies one of the basic enquiries in biology, especially in astrobiology. The present review intends to highlight the present possibility of testing whether the tape of evolution has been replayed elsewhere in the cosmos. We argue that achieving this objective is feasible with missions that are in principle, possible within the budgets that are available to any of the several national space agencies.

Since all forms of life known to us are terrestrial organisms, it is reasonable to question whether the universality of the science of biology is a valid research objective (Dawkins 1983; Akindahunsi & Chela-Flores 2004). The complementary nature of chance (contingency) and necessity (natural

selection as the main driving force in evolution) is relevant for astrobiology. Independent of historical contingency, natural selection is powerful enough for organisms living in similar environments to be shaped to similar ends. Our examples will favour the assumption that, to a certain extent and in certain conditions, natural selection may be stronger than chance (Conway-Morris 1998, 2003). We raise the related question of the possible universality of biochemistry, one of the sciences supporting chemical evolution.

Beyond the specialists of the theory of evolution the question of the relative importance of chance and necessity was brought to the attention of a large number of scientists by a well-known book (Monod 1971). The main issue is which features of the history of life are inevitable and which are highly contingent and, therefore, unpredictable. There is a broad list of publications addressing this issue. Following the publication of a series of books (de Duve 1995, 2002, 2005), some especially interesting discussions have been published. These books, and the ones cited above, have discussed extensively the question of the relative importance of contingency and convergence (Knoll 1995; Foote 1998; Szathmari 2002; Erwin 2003; Penny 2006). We begin the next

section by discussing some evidence that shows that, in spite of the intrinsic contingency of Darwinism, sometimes history tends to repeat itself during the course of evolution. Later, we explore the consequences of the hypothesis that such repetitions have in the search for life in the Universe.

Evolutionary history sometimes tends to repeat itself

The phenomenon of convergence occurs at various levels, such as in morphology, physiology, behaviour and even at the molecular level. Specifically, deep insights can be drawn from the neurosciences. The comparative approach of modern evolutionary neurobiology has been discussed in detail (Gazzaniga *et al.* 1998). Neuroscientists often work with animals other than humans to discover the principles of neural organization ('the comparative approach'). Homology refers to a structure, behaviour or even a gene that has been retained from a common ancestor. A clear example of homology is a wing of a bat, as well as the hand of a human; both of them have a common evolutionary descent. What is more interesting from our point of view is that the wing of a bat and the wing of an insect are not homologous, but they are examples of evolutionary convergence. (These structures look the same but do not have a common descent.) Examples of convergent evolution in the brain will be reviewed below. What we learn from them is that they demonstrate the limited and rigid rules by which brains evolve. Indeed, we can go further by recognizing that evolutionary convergence allows the examination of limitations inherent in the construction of nervous systems.

For these reasons, evolutionary convergence is, consequently, a significant phenomenon that should be discussed in the context of the universality of biology (namely, for demonstrating that biology is a science that is not only confined to the Earth biota, and hence it is a science of universal validity). The topic of the repetition of evolutionary history will be illustrated below with two examples taken firstly from the evolution of the brain and secondly from biochemistry.

We begin, as mentioned earlier, with an example of the brain in the dolphin (Krubitzer 1995; Manger *et al.* 1998). Although evolution has been associated with a 'tinkerer', detailed considerations of the products that evolution constructs point out that there are a limited number of underlying mechanisms that are accessed for building brains. The unit in question is a 'module', that is, a structure that not only occurs in large-brained mammals, such as dolphins and humans, but is also similar to that which occurs in small-brained mammals, such as the mouse. This suggests that module size is preserved by evolution across species. The implication of this remark is that, in the course of evolutionary history, repetition, in fact, does occur. In other words, evolutionary history tends to repeat itself. We can go further: these examples (and many others that we have not included for lack of space) suggest that the human brain is enslaved within the same genetic constraints as the brains of other

mammals. Consequently, its future evolution will be expected to follow constraints imposed on evolving nervous systems that are gradually being discovered by comparative neuroscience studies that have exposed similarities in cortical organization across species (Krubitzer & Khan 2003). The mechanisms for possible changes are guided by the same mechanisms that were responsible for the overall structure of other mammals. To sum up, many structures, some of which had previously been assumed to be homologous, have evolved many times independently. These studies demonstrate that evolutionary convergence in brain anatomy and function is widespread (Nishikawa 2002).

There is an analogous illustration for the widespread occurrence of evolutionary convergence in biochemistry: Darwinian evolution has been shown to follow only very few mutational paths to fitter proteins. In this case, once again contingency is limited by a diverse variety of constraints that are imposed on the evolutionary process. Such selective inaccessibility implies that the replaying of the tape of life at the biochemical level might make protein evolution not only repetitive, but even predictable (Weinreich *et al.* 2006). As we are assuming that evolutionary convergence is a widespread phenomenon in (universal) biology, we do not dwell on the question of whether other life uses some other structure. Indeed, the work of Weinreich *et al.* provides another example that the number of mechanisms that are accessed by natural selection is, in a number of cases, a limited set. We should compare this result from biochemistry with the above illustration that large brains are constructed in a similar fashion, independent of recent evolutionary history.

Multiple instances of 'history repeating itself' abound in the life sciences, for instance the science of palaeontology highlights the morphological analogies of organisms that live in similar environments in order to interpret their corresponding palaeo-environments (Ziegler 1983). The morphological similarities are evident in sessile benthos between the coral *Omphyma* and the bivalve *Hippurites*. Palaeontology also provides us with other remarkable examples of evolutionary convergence, as illustrated by the characteristic body shape of swimming vertebrates (the shark *Lamna* and the mammal *Focaena*, both of which are known morphologically as 'torpedo-type'). We have discussed organisms and anatomic structures that have been discovered in the construction of a biological system by the action of natural selection. Recently we, and other authors, have attempted to explore the implications of evolutionary convergence for the consideration of the emergence of biology anywhere in the Universe (Chela-Flores 2001, 2007). To put it another way, if the ubiquity of evolutionary convergence is correct, from the point of view of Darwinism, contingency and evolutionary convergence are opposite competing factors that have to be evaluated together, while considering the possibility that biology may arise in a niche, independent of the common descent of all of the biota that ever evolved on our planet. In the later part of this paper we discuss experiments intended to identify biological indicators elsewhere in our own Solar System.

Ubiquity of convergent evolution

Evolutionary convergence strongly advocates in favour of future space missions aiming to probe the universality of biology by careful tests based on the biochemistry that we already know. The universal nature of biochemistry has been discussed from the point of view of the basic building blocks (Pace 2001): one of the main points is that it seems likely that the building blocks of life anywhere will be similar to our own. Amino acids are formed readily from simple organic compounds and for a long time have been known to be present in extraterrestrial bodies, such as the Murchison meteorite. According to chemical analyses in this particular meteorite, we find basic molecules for the origin of life such as lipids, nucleotides and over 70 amino acids (Kvenvolden *et al.* 1971). Most of the amino acids are not relevant to life on Earth and may be unique to meteorites. This remark demonstrates that those amino acids present in the Murchison meteorite, which also play the role of protein monomers, are indeed of extraterrestrial origin. If the presence of biomolecules on the early Earth is due in part to the bombardment of interplanetary dust particles, comets and meteorites, then the same phenomenon could be taking place in any other solar system. In addition, chemical analysis has exposed the presence of a variety of amino acids in the Ivuna and Orgueil meteorites (Ehrenfreund *et al.* 2001). These comments can serve as support for the selection of experiments to be performed in the Solar System in the search for exobiology. This induces us to consider further the concept of convergence.

Divergence and convergence are two evolutionary processes by which organisms become adapted to their environments. Evolutionary convergence has been defined as the acquisition of morphologically similar traits by distinctly unrelated organisms (Austin 1998). Although many of the best-known examples of convergence are morphological, as mentioned above convergence occurs at every level of biological organization. However, molecular convergent evolution is most relevant for our enquiry into whether life is a universal phenomenon and, from the point of view of this review, we should also consider biochemical convergence in some detail. For instance, functional convergence refers to molecules that serve the same function but have no sequence or structural similarity and carry out their function by entirely different mechanisms. Despite the fact that alcohol dehydrogenases in vertebrates and *Drosophila* bear no sequence similarity, and their tertiary structures are different, they catalyse alcohol into acetaldehyde by different chemical reactions; they both remove hydrogen from alcohol (Doolittle 1994).

On the other hand, mechanistic convergence occurs when the sequence and structure of molecules are very different but the mechanisms by which they act are similar. Serine proteases have evolved independently in bacteria (e.g. subtilisin) and vertebrates (e.g. trypsin). Despite their very different sequences and three-dimensional structures, they are such that the same set of three amino acids forms the active site. The

catalytic triads are His 57, Asp 102 and Ser 195 (trypsin) and Asp 32, His 64 and Ser 221 (subtilisin), thus giving consensus catalytic triads of the form [Asp/Glu] His [Ser/Thr] (Tramontano 2002). Another example is structural convergence. This refers to molecules with very different amino acid sequences that can assume similar structural motifs, which may carry out similar functions. For example, α helices and β sheets can be formed from a number of different amino acid sequences and are found in many proteins. A further example is the remarkable similarity in fibronectin type III and immunoglobulin domains. They are composed of series of three- and four-stranded β sheets that are virtually identical in structure despite a lack of sequence similarity between these two molecules (Doolittle 1994).

Finally, we close this section with sequence convergence, which takes place in protein evolution. Indeed, one or more critical amino acids, or an amino acid sequence of two proteins, come to resemble each other owing to natural selection. If the putative ancestral amino acids at a particular site were different in the ancestors of two proteins that now share an identical residue at that location, then convergent evolution may have occurred. The most frequently cited case of convergence and parallelism at the sequence level is the digestive enzyme lysozyme in a number of unrelated animals. This group includes the langur (a primate), the cow (an artiodactyl) and the hoatzin (a bird). All of these animals have independently evolved the ability to use bacteria in order to digest cellulose (Kornegay 1996; Zhang & Kumar 1997). Here, a few specific residues have evolved in convergence to allow digestion of cellulose-eating bacteria.

Our Solar System is not unique for favouring the emergence of life

By cosmic convergence we mean a series of well-established observations that point in the direction to show that our Solar System and its galactic neighbourhood are not unique in many respects that are particularly relevant for the emergence of life. In the present section we review a few of them to make our point sufficiently supported by numerous observations. Of paramount importance in this respect is the broad knowledge that we have gathered in the old subject of chemical evolution that has been well reviewed over the last decade as already mentioned above.

A few cases argue in favour of the conjecture of convergence at the cosmic level. First, nuclear synthesis is relevant for the generation of the elements of the periodic table beyond hydrogen and helium and, eventually, for the first appearance of life in solar systems. The elements synthesized in stellar interiors are required to make the organic compounds that have been observed in the circumstellar, as well as the interstellar, medium in comets and other small bodies. The same biogenic elements are also needed for synthesis of the biomolecules of life. Moreover, the spontaneous generation of amino acids in the interstellar medium is suggested by general arguments based on biochemical experiments: the study of amino acid residues of an interstellar ice analogue at

room temperature has yielded 16 amino acids, some of which are also found in meteorites (Muñoz Caro *et al.* 2002; also see Bernstein *et al.* 2002). These factors help us to understand the first steps in the eventual habitability of planets.

On the other hand, the concept of cosmic convergence has a second aspect that may be inferred from what we know about small bodies, such as the Murchison meteorite. These bodies may even play a role in the origin of life. According to chemical analyses this particular meteorite contains basic molecules that are needed for the origin of life, such as lipids, nucleotides and more than 70 amino acids (Cronin & Chang 1993). Most of the amino acids are not relevant to life on Earth and may be unique to meteorites. This demonstrates that those amino acids present in the Murchison meteorite, which also play the role of protein monomers, are indeed of extraterrestrial origin. In addition, chemical analysis has demonstrated the presence of a variety of amino acids in the Ivuna and Orgueil meteorites (Ehrenfreund *et al.* 2001). If the presence of biomolecules on the early Earth is due in part to the bombardment of interplanetary dust particles, comets and meteorites, then the same phenomenon could be taking place in other solar systems.

The interstellar medium provides yet another illustration of convergent phenomena that occur at a cosmic level. Indeed, solar systems, many of which are now known, originate from interstellar dust that is constituted mainly of the fundamental elements for life, such as carbon, nitrogen, oxygen, sulphur, phosphorus and a few others. Stars as they evolve and go through the main sequence of the Hertzsprung–Russell diagram expel their material into interstellar space in two different ways (Abell 1982). First, when stars of at least 0.4 solar masses exhaust their supply of hydrogen, their outer layers expand to form a red giant. Eventually the core is compressed enough to start helium fusion, gradually shrinking the star radius and increasing its surface temperature. After the star has consumed the helium at the core, fusion continues in a shell around a hot core of carbon and oxygen. After a series of intermediate steps the final stage is reached when the star begins producing iron. In relatively old and massive stars, a large core of iron accumulates in the centre of the star. An average-size star will then shed its outer layers as a planetary nebula. If what remains after the outer atmosphere has been shed is less than 1.4 solar masses, it shrinks to a white dwarf somewhat similar to the size of the Earth.

Second, in larger stars, if fusion continues until the iron core has more than 1.4 solar masses the core will suddenly collapse. The shockwave formed by this sudden collapse causes the rest of the star to explode in a supernova.

These supernova explosions are a source of enrichment of the chemical composition of the interstellar medium. In turn, these events provide new raw material for subsequent generations of star formation, which leads to the formation of planets. Late in their evolution, stars are still poor in some of the heavier biogenic elements (for instance, magnesium and phosphorus). Such elements are the product of nucleosynthesis triggered in the extreme physical conditions that occur in the supernova event itself. By this means, the newly

synthesized elements are disseminated into interstellar space, becoming dust particles after a few generations of star births and deaths (Greenberg & Mendoza-Gomez 1993). In both cases of the evolution of stars, heavy elements may be recycled to form new stars and terrestrial planets. In this sense there is universal convergence of terrestrial planet formation independent of a given solar system. To sum up, the ubiquity and common origins of the interstellar medium strongly suggest arguments in favour of the universality of biology for several reasons: the substantial work done by organic chemists known as chemical evolution argues in favour of the synthesis of amino acids in the interstellar medium (Bernstein *et al.* 2002; Muñoz Caro *et al.* 2002), as did occur in our own origins in the Solar System. Chemical evolution experiments have suggested that amino acids are so easy for nature to make that they must be the building blocks of choice for making living systems. We must underline the fact that since the epoch-making experiment of Stanley Miller to the present day, the evidence argues compellingly in favour of universal biochemistry (Pace 2001; Seckbach *et al.* 2004).

An additional case that argues in favour of convergence at a cosmic level is emerging from what we are beginning to learn about the origin of planetary systems around stars. Our Solar System formed in the midst of a dense interstellar cloud of dust and gas, essentially a circumstellar disc around the early sun. Some evidence suggests that this event was triggered by the shock wave of a nearby supernova explosion more than five billion years ago. Indeed, the evidence for this aspect of the origin of the Solar System is the presence of silicon carbide (carborundum, SiC) grains in the Murchison meteorite, a fact demonstrating that they are matter from a type II supernova (Hoppe *et al.* 1997). We may now be observing an extra-solar circumstellar disc around a young three-million-year-old sun-like star in the constellation Monoceros (Kerr 2002). Several earlier examples of circumstellar discs are known, including a significantly narrow one around an eight-million-year-old star. The narrowness of this disc suggests the presence of planets constraining the disc (Schneider *et al.* 1999). The following additional information further supports the arguments in favour of universal mechanisms of convergence in the formation of solar systems; that is, the matter of the original collapsing interstellar cloud does not coalesce into the star itself, but collapses into the spinning circumstellar disc, where planets are thought to be formed by a process of accretion. Some planetesimals collide and stay together because of the gravitational force. In addition, a variety of small bodies are formed in the disc, prominent among which are comets, asteroids and meteorites, completing the components that make up a solar system, as we know it. Finally, the fifth example of ‘cosmic convergence’ is provided by the convergent origin of hydrospheres and atmospheres. The earliest preserved geologic period (the lower Archaean) may be considered as representing the tail end of the ‘heavy bombardment period’. During that time, various small bodies, including comets, collided frequently with the early precursors of the biomolecules that eventually ignited the evolutionary process on Earth and in its oceans. In

addition, comets may be the source of other volatile substances significant to the biosphere, as well as the biochemical elements that were precursors of the biomolecules (Delsemme 2000). Collisions with comets, therefore, are thought to have played a significant role in the formation of the hydrosphere and atmosphere of habitable planets, including the Earth. The source of comets is the Oort cloud and Kuiper belt. These two components of the outer Solar System seem to be common in other solar systems. Hence, in the sense of the above-mentioned examples, we recognize evolutionary convergence on a cosmic scale (Chela-Flores 2007).

Can the universality of biology be tested?

Testing the nature of biology within the Solar System is gradually becoming more feasible with the available technology. This is especially true, owing to the new technology that is currently being developed. The search for life elsewhere in the Universe is a time-honoured research that has been called 'bioastronomy'. A large number of researchers have followed up this discipline since the middle of the last century. The SETI project (the initials stand for the 'Search for Extraterrestrial Intelligence') has advanced at a vertiginous pace (Ekers *et al.* 2002). With the tools that will be available in the near future there will be more definite searches specifically focusing on likely exo-planets. For instance, the Convection Rotation and Planetary Transits (COROT) mission after 2007, which is supported by CNES, ESA, Austria, Spain, Germany, Belgium and Brazil, will search for rocky Earth-like planets. Later on, the ESA Darwin mission will be aimed at the search for planets, and possible biosignatures on them, in the mid-infrared. It will be possible with Darwin to study nearby terrestrial exo-planets (<25 pc) that will be orbiting stars within their Habitable Zone. Darwin is expected to launch in the 2015 time frame. However, we should stress that the present techniques do not allow detection of Earth-like planets and none have been found among the couple of hundred planets detected so far. Yet it is inspiring to look forward to NASA's Kepler Discovery mission, which is a space-borne telescope designed to survey distant stars to determine the prevalence of Earth-like planets. Scheduled to launch in 2008, Kepler will hunt for planets indirectly using a 1 m diameter telescope (photometer) to measure the small changes in brightness caused by transits. A transit occurs each time a planet crosses the line-of-sight between a planet's parent star, which it is orbiting, and the observer. Therefore, when a transit happens, the planet blocks some of the light from its star, resulting in a periodic dimming. This periodic signature is used to detect the planet and to determine its size and its orbit.

In view of such technological promise, the central problem of astrobiology (the existence of life elsewhere in the Universe) is no longer the exclusive domain of organic chemistry. This well-established field of 'chemical evolution' was developed throughout the last century, after the pioneering work of Alexander Ivanovich Oparin in the 1920s (Ponnamperuma & Chela-Flores 1995). This field has been

extensively reviewed over the last decade, not only in the book already mentioned published in collaboration with Cyril Ponnamperuma, but also in the Trieste and Caracas series (Ponnamperuma & Chela-Flores 1993; Chela-Flores *et al.* 1995; Chela-Flores & Raulin 1996, 1998; Chela-Flores *et al.* 2000, 2001; Seckbach *et al.* 2004). We expect that radio astronomy and space exploration will be an ever-increasing stronger partner with a significant relevant role to play.

There are significant strategies for identifying those places where future landers could search for biosignatures. The Jovian satellite Europa is the most appealing site for the discovery of extraterrestrial life in our cosmic neighbourhood. A key factor in this enterprise has already been provided by the discovery of sulphur patches on the icy surface of this satellite by the Galileo mission. The discovery is significant due to several additional measurements that strongly suggest the presence of an internal deep ocean, a potential habitat for extremophilic (cryophilic) microorganisms. The evidence from the Galileo Near-Infrared Mapping Spectrometer (NIMS) for the presence of sulphur compounds has been discussed in detail in our previous paper (Chela-Flores 2006). The most likely sites would be where the salt deposits, or organics, are concentrated, as suggested by the NIMS data. For instance, the search for biosignatures could focus on the area north of the equatorial region, between 0° and 30°N and between the longitudes 240° and 270° (cf. McCord *et al.* 1998, Fig. 2A). However, a more intriguing and smaller patch would be the narrow band with a high concentration of non-ice elements that lies east of the Conamara Chaos, between the Belus and Asterius lineae, namely, between 18° and 20°N, and longitudes 198° and 202° (cf. McCord *et al.* 1998, Fig. 2D). Definite answers can be searched for *in situ* on the icy surface with gas chromatography–mass spectrometry instrumentation for the corresponding measurements with the help of biogeochemistry, especially with the $\delta^{34}\text{S}$ parameter that is defined as

$$\delta^{34}\text{S} = \left[\frac{(^{34}\text{S}/^{32}\text{S})_{\text{sa}}}{(^{34}\text{S}/^{32}\text{S})_{\text{st}}} - 1 \right] \times 10^3 \quad [\text{‰CDM}].$$

Its value is close to zero when the sample coincides with the corresponding value of the Canyon Diablo meteorite (CDM), a trillite (FeS) that was found in a crater north of Phoenix, AZ. This parameter allows a comparison of a sample (sa) with the standard (st) CDM. The relevant terms are the dominant sulphur isotope (^{32}S) and the next in abundance (^{34}S). In fact, $(^{34}\text{S}/^{32}\text{S})_{\text{st}}$ coincides with the average terrestrial fraction of the two most abundant isotopes of sulphur. For the specific measurements on Europa's surface where the delta $\delta^{34}\text{S}$ parameter is relevant, we refer the reader to our previous paper (Chela-Flores 2006). Measurements by mass spectrometry are needed. In a feasible mission to Europa they are possible as discussed earlier (Chela-Flores 2006), owing to miniaturized equipment that is already in existence.

A specific example is provided by mass spectrometry on a possible future lander on Europa. At this stage it is possible to put forward the best possible landing site. We have suggested that at the 'patch' found in the European surface coordinates

200°W, 20°N (longitude and latitude, respectively) there is a valid scientific way of testing biogenicity through isotopic fractionation that may have occurred on sulphur patches on the European icy surface (Singer 2003; Bhattacharjee & Chela-Flores 2004). The evidence from microbiology and developmental biology militates in favour of the emergence of a nervous system. Indeed, at the level of diploblastic animals (cnidarians such as the common jellyfish), there is considerable evidence from electrophysiology that at such a low level of evolution nervous 'nets', rather than nervous systems, arise. Moreover, the evidence reported in Table 1 of a previous paper (Chela-Flores (2003), where full references to the original neuroscience literature are given; cf. also Chela-Flores (2001, ch. 12) and Villegas *et al.* (2000)) suggests that the further evolution beyond nervous nets to the appearance of cerebral ganglions inexorably takes place in the lowest multicellular organisms, such as, for instance, in annelids, the ancestors of common worms. Once again, as soon as the diploblastic/triploblastic barrier has been crossed, cerebral ganglions appear, leading to the early emergence of primitive brains rather than ganglions for more evolved multicellular animals such as the early vertebrates that arose during the Cambrian. New molecular neurobiology experiments are attempting to confirm early results of an electric signalling system that were found in *R. dawsoni*, a species amongst the most ancient sponges and, therefore, amongst the most ancient metazoans (Villegas 2007).

As a guideline in our search for a way out of the impasse created by still not having had a first contact with an extra-terrestrial civilization, 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: 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. Everyone agrees that Newton's theory of gravitation can be extrapolated without any difficulty throughout the Universe, except for the corrections implied in the theory of general relativity. The case of extrapolating the theory of biological evolution throughout the cosmos requires more care and is evidently 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 (Aretxaga 2004). The role of randomness has been qualified since Darwin's time. The role of chance is implicit in *The Origin of Species*. We have also seen that molecular biology constrains chance. Evolutionary convergence is an additional factor to take into account, as illustrated with the above examples of neuroscience and biochemistry. In summary, Darwinian contingency is constrained. Evolution often 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 and are supplied with analogous

abundances of the chemical elements. We are already gathering information on a significant number of Jupiter-like planets around stars in our cosmic neighbourhood. Such planets arise from sub-nebulae 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 in our Solar System has a large suite of satellites. Factors giving rise to atmospheres in satellites of the giant planets, such as Saturn, are known. Titan, for instance, has an atmosphere that was produced by out-gassing, combined by seeding of volatiles by comets carrying a fraction of water ice. Evidence is leaning in favour of the existence of Jovian planets in our Galaxy 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 whether tidal heating could produce hydrothermal vents capable of giving rise to life, but the case in favour of this hypothesis is strong (Thomson & Delaney 2001). 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 in those extra-solar cases on a finite number of similar environments.

Once again, in cosmochemistry, similar chemical elements will be available for chemical evolution. We have also learnt that there are no laws in chemical evolution that are specific to the Earth; it is reasonable to hypothesize that biological evolution will follow, once the molecules of life have emerged from chemical evolution. 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 the evolution of life on Earth. For these reasons we have advocated a possible approach to the problem of the distribution of life in the Universe, namely a search at the cellular level in our Solar System. In other words, the search for extraterrestrial microorganisms is a worthwhile research program in future space exploration (Chela-Flores 1998, 2000).

Discussion

In this relatively short review we have not attempted to be exhaustive on the question of convergence, either biological or cosmic. Indeed, it is not even necessary, as there are excellent texts and papers that have already achieved this purpose. (Excellent books are already available, and were mentioned above.) The examples cited are only meant to frame the question that the search for life makes sense with the intuition from biology and physics that we have learnt on Earth (convergence in biology and physics). It is necessary to make the concept of convergence in physics sharper, and the first steps towards this have been taken elsewhere (Chela-Flores 2007).

The inevitability of the emergence of particular biological properties is a phenomenon that has been recognized by students of evolution for a long time. It has been referred to in the present paper as 'evolutionary convergence'. This phenomenon has been illustrated with examples from

biochemistry and other branches of the life sciences. The assumed universality of biochemistry suggests that, in Solar System missions, biomarkers should be selected from standard biochemistry.

The main point of this review has been to discuss the fact that evolution itself is the result of two competing factors: contingency and convergence. A substantial body of evidence argues in favour of evolutionary convergence having played a major role in the Earth biota during its ascent from bacteria to humans. The concept of convergence in the space sciences, discussed above, argues in favour of biology (including astrobiology) being a universal science.

The examples that we have cited highlight the ubiquity of evolutionary convergence. What does it mean within the framework of Darwinism? Indeed, the ubiquity of evolutionary convergence argues against biological diversity being unique to Earth and that within certain limits the outcome of evolutionary processes might be predictable. This remark does not contradict the question recalled at the beginning of this review, namely that if we were able to replay the tape of evolution from the Cambrian onwards, the likelihood of present-day organisms existing would certainly be different. However, this is only part of what is implied in Darwinism. Replaying the tape of life might be significantly repetitive (Weinreich *et al.* 2006). Recent examples abound. We discussed at the beginning of this review the fact that the human brain seems to have the same genetic constraints as the brains of other mammals. Consequently, our expectation for its future evolution is that the brain will follow predictable paths that are guided by the same mechanisms responsible for the overall structure of other mammals. Clearly, however, the precise specializations that may emerge cannot be known (Krubitzer & Khan 2003).

These Darwinian arguments contribute to providing a cornerstone for our thinking on the search for evolutionary biosignatures during the exploration of the Solar System. Finding traces of life in any of the candidate sites that are known to space geophysicists, such as Europa, Enceladus, Titan or Mars, would add arguments towards obtaining further insights into the universality of biology.

This review has intended to provide a framework within Darwin's theory of evolution for a preliminary test of the conjecture of the universality of biology. Such a test would be feasible with experiments on the European surface, involving evolutionary biosignatures (biogenicity of sulphur on the patches of the icy surface). This aspect of the exploration for life in the Solar System should be viewed as a complement to the astronomical approach to the search for evidence of the later stages of the evolutionary pathways towards intelligent behaviour (the SETI project).

The set of hypotheses that have been put forward in this review are clearly subject to experimental refutation with experiments that are feasible with the current technology available to the main space agencies. We have argued that convergence provides a rationale for astrobiology and, as one of its most recent branches, is currently being pursued by a number of national space agencies.

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