

Fitness of the Cosmos for Life

Fitness of the cosmos for the origin and evolution of life: from biochemical fine-tuning to the Anthropic Principle

Julian Chela-Flores

The Abdus Salam International Centre for Theoretical Physics

Trieste, IT and

Institute of Advanced Studies

Caracas, VE

chelaf@ictp.trieste.it

The boundaries of philosophy, science, and theology

Some of the deeper questions that humans have raised are not always answerable within the boundaries of science. Instead, philosophers and theologians have approached such questions within their own domains of competence. One such example is provided by the question of purpose in evolution (see the discussion below). Indeed, the concept of purpose in a general sense may be understood as something that one sets before oneself as an object to be attained, an aim to be kept, a plan to be formulated. In attempting to give an answer to the question of “purpose in nature,” we should discuss the main components of human knowledge in an integrated way, so as to ask the right questions in the right field of knowledge. This approach should encourage us to provide appropriate answers that are reasonable within philosophy, science, or theology. At this juncture, it may be also argued that the task of a scientist should be independent of that of the other areas of human culture (Russell, 1991: 13). On the other hand, it is surely useful to be aware that this view of the role of science that is “divorced” from both philosophy and

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natural theology can also be seen from a different point of view (Townes, 1995: 166): Because science and religion are evolving and are similar in their search for truth, convergence of these independent searches for truth may occur in the future.

I wish to address some questions in philosophy and theology that are pertinent to the main subject of this chapter. In order not to go beyond the natural boundaries of either science or theology, I will discuss contemporary attempts to encompass Darwinian evolution in a natural theological context. To meet this objective, we need some definitions to make this chapter self-contained.

First, *teleology* may be considered in two separate ways: Either it is a doctrine according to which everything in the cosmos has been designed with humans in mind, or it can be interpreted as a theory of purposiveness in the cosmos (namely, phenomena that are to be explained in terms of its purpose, rather than by initial causes). This latter concept is intimately related to the Anthropic Principle, either as employed in physics or in biochemistry. Teleology is also related to various interpretations of fine-tuning in phenomena such as the nuclear reaction of beryllium atoms in the production of carbon, as originally pointed out by Fred Hoyle (Hoyle, 1975: 401-02).

Second, the notion of *process* dominates the work of three philosophers of the last century: Louis Bergson (1859-1941), Samuel Alexander (1859-1938), and Alfred North Whitehead (1861-1947) (see Ayer, 1982: 208-09). In passing, it is perhaps worth noting that process theology is based on the metaphysics of Whitehead, who rejected Divine Action in terms of causality, proposing that God acts persuasively in all events, but not

necessarily in determining their character. Specifically, Whitehead pointed out the incoherence of belief in a lifeless universe.

Elsewhere in this book, Haught has emphasized God as the sole ground for the world's being (see also Haught, 1998: 393-418). This approach to natural theology leads him to explain the world in terms of evolution, as understood within the Darwinian tradition (Russell, 1996: 1-31). Russell focuses on features of process thought. This philosophical system is considered to be particularly helpful in the task of constructing an evolutionary theology that may throw some further light on Darwinism.

A far-reaching implication of the possibility of interpreting the evolutionary aspects of Darwinism within theology is that the evolutionary process begins at the molecular level of biochemistry. In fact, such "chemical" evolution is a time-honored discipline that has been studied extensively in the past, particularly during the last decade of the last century (e.g., Ponnampereuma and Chela-Flores, 1993; Chela-Flores et al., 2001). In this chapter, I endeavor to show that fine-tuning in biochemistry is a well-defined problem. Its evolutionary aspects should, in principle, be able to be integrated into a framework of natural theology, for instance in approaches such as kenotic process theology.

Process philosophy, or "process thought," attempted to provide a common metaphysical basis for discussions of science and religion. Some criticisms have been raised in the past (Polkinghorne, 1996: 28): If physics is to be appropriate for process thought, this school of philosophy has to face an ongoing debate. In particular, continuity seems to be intrinsic to quantum mechanics (for example, the Schrödinger equation is a differential

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equation). For Polkinghorne, at least, the mathematics of process thought should be that of “difference” equations, instead of “differential” equations (with their implied underlying continuity).

On the other hand, we should keep in mind deeper issues that are currently under debate as quantum gravity aims to provide a coherent theory of spacetime. Spacetime is a dynamic entity, and as such it would have quantum properties (Rovelli, 2000: 3776-3800). Both current and future developments in theoretical physics have to investigate the concept of *discrete* excitations of space itself. Thus, process thought, as a philosophical system, cannot be ruled out at present because of an unfinished debate in theoretical physics.

To complete our discussion of contemporary attempts to encompass Darwinism in a natural theological context, we ask whether there is evidence of purpose in the cosmos. If we allow the simultaneous approaches of philosophy, theology, and science, it seems possible to reconsider the question that has been raised in the past: Is there evidence of purpose in the cosmos? And, in particular, Is there any evidence of purpose in biochemistry?

We can consider how the cosmos itself is well-fitted for the origin and evolution of life. I will discuss how the combined approaches of philosophy, science, and ultimately natural theology can help us to begin to discuss the intelligibility of the universe in a rational way. Care is needed in addressing the right questions within their corresponding cultural domain.

First, we consider the origin and evolution of intelligent behavior in the cosmos, examining the case of life on earth. As already pointed out above, investigations of the evolution of life on earth (Darwinism) can be incorporated in natural theology (process theology), at least in principle. The subsequent arguments in this chapter, within the boundaries of science, should, I hope, be useful for their interpretation in terms of theological issues.

Biochemical fine-tuning and fitness of the cosmos for life

Our starting point for studying the fitness of the cosmos for the origin and evolution of life is Lawrence J. Henderson's influential *The Fitness of the Environment* (1913). As a graduate of and professor at Harvard University, Henderson's main interests ranged widely, and he became a physiologist, chemist, biologist, philosopher, and sociologist. He discussed the question of teleology in biochemistry to give some rationale to the question of the fitness of the environment for the evolution of life. For many chemical compounds, he discussed the difficulties that the evolution of life would have encountered had these compounds not been freely available in the environment. One obvious example used by Henderson was water, the search for which even today is a main objective of our explorations of the solar system, especially Mars, Europa, Titan, and Enceladus (the tiny Saturn moon).

Today, we need to search the roots of Henderson's biocentrism at the molecular level. In fact, fine-tuning in biochemistry is represented by the strength of the chemical bonds that makes the universal genetic code possible. Neither transcription nor translation of the

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messages encoded in RNA and DNA would be possible if the strength of the bonds had different values. Hence, life, as we understand it today, would not have arisen.

In this chapter, I will argue in favor of the fitness of the cosmos for the origin and evolution of life without touching on the question of teleology. Instead, we approach the subject by considering biological evolution in the universe, as well as the evolution of the structure of the cosmos itself. I will touch on the evolution of solar systems, interstellar matter, and finally various aspects of the cosmos—all in relation to the emergence of life. However, I hasten to point out that arguments based on science can nevertheless be a source of inspiration for reconsidering the bases of natural theology. I will argue that the fitness of the universe for the origin and evolution of life can be best understood not only through convergence in biochemistry, but also through a range of convergences based on observations of phenomena in the space sciences.

The Weak Anthropic Principle in cosmology and biochemistry

In cosmology or biology, we may inquire whether general mechanisms (for instance, natural selection and adaptive radiation), as well as special values of some physical constants, could be interpreted together in natural theology as indications of purpose. The example of “fine-tuning” in physics has led to a weaker and a stronger version of the Anthropic Principle, which is concerned with the question of the bases of life, particularly intelligent life, in the cosmos. I have no difficulty in accepting what has come to be known as the “Weak Anthropic Principle” in physics:

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Change the laws (and constants of nature), and the universe that would emerge most likely would not be compatible with life.

Biochemistry offers a clearly analogous statement:

First omit the observed cosmic abundance of the biogenic elements that are favorable to life. Then omit the environments (earth-like planets or Europa-like satellites) that favor evolution and adaptive radiation. The consequence of omitting both factors is that life most likely would not arise.

However, difficulties certainly would arise, both in cosmology as well as in biology, if we allowed some degree of teleology to be brought into the argument. Here, of course, I am referring to formulation of the “Strong Anthropic Principle”:

- The laws of nature and the physical constants were established so that human beings would arise in the universe.
- The distribution of earth-like environments and Europa-like satellites was laid out so that not only life, but at least in certain circumstances human beings, would also arise in the universe.

The general mechanisms of nature, according to the evidence that we can infer from the biota of earth, which by now is at least 3 billion years old, imply that the evolution of intelligent behavior seems inevitable. What is not evident is the inevitability of the emergence of human beings.

The intimately related concepts of the Anthropic Principle and fine-tuning in living systems (Carr and Rees, 2003: 1-8) are topics that would be simpler to understand with knowledge of more than a single instance of emergence of life on earth. On the other hand, our religious traditions go back to Jewish theology: A sole omnipotent God created heaven and earth, and subsequently life on earth. This view of our origins has traditionally been referred to as the “First Genesis.” With the emergence of astrobiology (Chela-Flores, 2001), we can start to explore the possibility of the occurrence of a “Second Genesis”—namely, whether the evolution of intelligent behavior is inevitable in an evolving cosmos, given the present laws of cosmology (general relativity) and the general mechanisms of biological evolution (natural selection and adaptive radiation). If we were to change these laws and mechanisms, the arguments supporting the inevitability of the evolution of intelligent behavior would not stand, and thus the evolution of intelligent beings would not necessarily take place. This aspect of evolution has clear implications for the Weak Anthropic Principle.

A first aspect of convergence: cultural convergence

In the search for answers that go beyond the boundaries of a given area of human culture, we should first consider whether the various approaches would ever converge. The concept of convergence enters our discussion in three different contexts. In this section, I consider convergence in different cultural areas (Townes, 1995: 166). The other two aspects that are discussed in the following two sections are (1) convergence at a cosmic level, a subject that is essentially based in the space sciences, and (2) convergence in biology, a topic that is central to understanding Darwinian evolution.

Both science and religion are concerned with the common understanding of life in the universe. Because they largely address the same questions, we would expect that both aspects of human culture should at some point converge. With subsequent progress in philosophy, science, and theology, convergence seems unavoidable, although human culture does not seem to show any evidence of convergence at present. The status of the relationship between these three disciplines—philosophy, science, and theology—has been discussed in the past (John Paul II, 1992: 1). In this chapter, an integrated approach to the questions regarding the fitness of the universe for the origin and evolution of life aims to avoid a splintered culture.

A second aspect of convergence: convergence at the cosmic level

In this section, I will discuss five cases of convergence at the cosmic level. First, from organic chemistry we know that 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 for making 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 experimentation: The study of amino acids in the room-temperature residue of an interstellar ice analog has yielded 16 amino acids, some of which are also found in meteorites (Muñoz Caro et al., 2002: 403-06; also see Bernstein et al., 2002: 401-03). 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 the small bodies, such as the Murchison meteorite. These bodies may even play a role in the origin of life: According to chemical analyses in this particular meteorite, we find basic molecules that are needed for the origin of life such as lipids, nucleotides, and more than 70 amino acids (Cronin and Chang, 1993: 209-58). 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: 2138-41). 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.

Interstellar gas provides yet another illustration of the convergent phenomenon that occurs 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 of life, such as C, N, O, S, P, and a few others. Just before a star explodes into a supernova, all the elements that have originated in its interior as a result of thermonuclear reactions are expelled, thus contributing to the interstellar dust. The star itself collapses under its own gravity, compressing its matter to a degenerate state; the laws of microscopic physics eventually stabilize its collapse into a white dwarf. Stellar evolution of stars more

massive than the sun is far more interesting: After the star has burnt out its nuclear fuel, a catastrophic explosion follows in which an enormous amount of energy and matter is released. These supernovae explosions are the source of enrichment of the chemical composition of the interstellar medium. This chemical phenomenon, in turn, provides 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.

An additional case that argues in favor 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 disk 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, some evidence indicates 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: 1314-17). We may now be observing an extrasolar circumstellar disk around a young three-million-year-old sun-like star in the constellation Monoceros (Kerr, 2002: 2312-13). Several earlier examples of circumstellar disks are known, including a significantly narrow one around an eight-million-year-old star. The narrowness of this disk suggests the presence of planets constraining the disk (Schneider

et al., 1999: L1217-30). The following additional information further supports the arguments in favor 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 disk, 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 disk, prominent among which are comets, asteroids, and meteorites, completing the components that make up a solar system.

Finally, the fifth example of what I have called “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. Collisions with comets, therefore, are thought to have played a significant role in the formation of the hydrosphere and atmosphere of habitable planets, including 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 this cosmic sense, we recognize evolutionary convergence.

A third aspect of convergence: the case for convergence in biology

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The question of evolutionary convergence in the context of the life sciences has been discussed extensively (Conway Morris, 2003 and this volume; Chela-Flores, 2001: 149-62; 2003: 307-12; 2006, in press; Akindahunsi and Chela-Flores: 2004: 135-38). We are assuming that natural selection is the main driving force of evolution in the universe, a hypothesis made earlier elsewhere (Dawkins, 1983: 403-25). For these reasons, it is relevant to question whether local environments that were favorable for the emergence of life on the early earth were at all unique, occurring exclusively in our own solar system. Another view on the universal validity of biology in the cosmos has been advanced in the context of the basic building blocks (Pace, 2001: 805-08): It seems likely that the basic building blocks of life anywhere will be similar to our own. Amino acids are readily formed from simple organic compounds and occur in extraterrestrial bodies, such as meteorites. Functions that are suggested as being common to life elsewhere in the cosmos serve to capture adequate energy from physical and chemical processes to conduct the chemical transformations that are necessary for life: lithotrophy, photosynthesis, and chemosynthesis. Other factors that argue in favor of the universality of biochemistry are physical (temperature, pressure, and volume) and genetic constraints (see below).

In general, we may say that features that become more, rather than less, similar through independent evolution will be called “convergent.” In fact, convergence in biology is often associated with similarity of function, as in the evolution of wings in birds and bats. New World cacti and the African spurge family provide an example. Some other examples are the euphorbs, such as *Euphorbia stapfii*, and some members of the Madagascar Didieraceae (*Didiera madagascariensis*). These plants are similar in appearance, being succulent, spiny, water storing, and adapted to desert conditions

(Tudge, 1991: 67; Nigel-Hepper, 1982: 81). However, they are classified in separate and distinct families, sharing characteristics that have evolved independently in response to similar environmental challenges. Hence, we may say that this is a typical case of convergence.

When we look at convergence at the biochemical level, we can further document the general question of the evolution in the life sciences. Convergent evolution is manifest at the active sites of enzymes and in whole proteins, as well as in the genome itself:

- The northern sea cod (*Boreogadus saida*) is an economically important marine fish of the family Gadidae found on both sides of the North Atlantic. The distantly related order Perciformes with its suborder Percoidei contains the sea basses, sunfishes, perches, and, more relevant to our interest, the notothenioid fishes from the Antarctic (*Dissotichus mawsoni*). In spite of their distant relationship with cods, they have evolved the same type of antifreeze proteins, in which the amino acids threonine, alanine, and proline repeat (Chen et al., 1997: 3817-22). These proteins are active in the fish's blood and avoid freezing by preventing the ice crystals from growing. The Antarctic fish protein arose over seven million years ago, while the Arctic cod first appeared about three million years ago (both species arose in different episodes of genetic shuffling).
- The blind cavefish *Astyanax fasciatus* are sensitive to two long-wavelength visual pigments. In humans, the long-wavelength green and red visual pigments diverged about thirty million years ago. The mammalian lineage diverged from

fishes about four hundred million years ago, but a recent episode in evolution has provided fish multiple-wavelength-sensitive green and red pigments. Genetic analysis demonstrates that the red pigment in humans and fish evolved independently from the green pigment by a few identical amino acid substitutions (Yokoyama and Yokoyama, 1990: 9315-18), a clear case of evolutionary convergence at the molecular level.

- Convergence may also occur 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, in each the same set of three amino acids form the active site. The catalytic triads are His 57, Asp 102, and Ser 195 (trypsin) and Asp 32, His 64, and Ser 221 (subtilisin) (Doolittle, 1994: 15-18).

Evolutionary convergence in biology has been best documented at the level of animals. The evolutionary biology of the Bivalvia, both at the level of zoology and paleontology, provide multiple examples of convergence and parallel evolution, a fact that makes the interpretation of their evolutionary history difficult (Harper et al., 2000: 1-494). Specific examples of convergence in mollusks have been pointed out in the case of various families of the gastropods (camaenid, helminthoglyptid, and helcid snails). The shells of the camaenid snails from the Philippines and the helminthoglyptid snails from Central America resemble each other and also members of European helcid snails. These distant species, in spite of having quite different internal anatomies, have grown to resemble

each other morphologically in response to their environment. In other words, in spite of considerable anatomical diversity, mollusks from these distant families have come to resemble one another in terms of their external calcareous shell (Tucker Abbott, 1989: 7-8).

In addition, we should recall that the Passeriformes (including swallows) may be confused with Apodiformes (including swifts), but are not related to them. Swallows and swifts provide a classical example of evolutionary convergence. Although unrelated, swallows are generally similar to swifts in size, proportion, and aerial habits (Clench and Austin, 1983: 1052-66). Members of these two orders differ widely in anatomy, and their similarities are the result of convergent evolution on different stocks that have become adapted to the same lifestyles in similar ecosystems for both species.

Can convergent pathways of evolution in the cosmos be foreseen?

Above I have argued that fine-tuning in biochemistry is represented in molecular biological terms by the strength of chemical bonds that make the universal genetic code possible. The messages coded in RNA and DNA would not be possible if the strength of the bonds had different values. Hence, life, as we understand it today, would not have arisen. Subsequent evolutionary stages beyond molecular evolution in biochemistry (i.e., beyond chemical evolution of the building blocks of life) will depend on certain factors that can be documented with further research in the geologic record of hydrothermal vent communities and with the exploration of the solar system. I will review some of them, beginning with the geologic record. Some evidence indicates that once life originates, provided sufficient (geologic) time is available, evolution will provide living organisms

with the opportunity to occupy every conceivable environment. This notion further favors the hypothesis that once life appears at a microscopic level on a given planet or satellite, the eventual evolution of intelligent behavior is just a matter of time.

The inevitability of some of the earliest stages of the evolution of life on earth can be illustrated with careful analysis of the geologic record. For instance, Cambrian fauna, such as lamp-shells (inarticulate brachiopods) and primitive mollusks (Monoplacophora), were maintained during Silurian times by microorganisms that lived in hydrothermal vents (Little et al., 1997: 146-48). Many examples of such fossils have been retrieved from the Silurian Yaman Kasy sulfide deposit. This volcanogenic site is located at the Orenburg district (southern Urals, Russia). In modern vent communities, monoplacophorans have been recovered at the Mid-Atlantic Ridge (37° 50' N), and brachiopods from mid-ocean ridges are also recorded. However, taxonomic analysis of Cenozoic fossils suggests that shelly vent taxa are not ancestors of modern vent mollusks or brachiopods (Little et al., 1998: 259-70). We may conclude that modern vent taxa support the hypothesis that the vent environment is not a refuge for evolution.

In fact, evidence exists that since the Paleozoic and through the Mesozoic era, taxonomic groups have moved in and out of vent ecosystems through time—no single taxon has been unable to escape evolutionary pressures. Some independent support for deep-water extinction has also been presented (Jacobs and Lindberg, 1998: 9396-401). These findings rule out the possibility that deep-sea environments are refuges against evolutionary pressures. In other words, the evidence so far does not support the idea that there could be environments where ecosystems might escape biological evolution, even

at the apparently unassailable depth of the oceans. This gives considerable support to the hypothesis that any microorganism, in whatever environment on earth or elsewhere, would be inexorably subject to evolutionary pressures.

As I have shown above, fossils from Silurian hydrothermal-vent fauna demonstrate that species have become extinct in locations that at first sight seem to be far removed from the pressures of evolutionary forces. Given that there are no refuges against evolution, we can raise the question whether over geologic time it was inevitable that the most primitive cellular blueprint bloomed into full eukaryogenesis and beyond, along convergent evolutionary pathways, ultimately to organisms displaying intelligent behavior (Chela-Flores, 1998: 79-99).

To investigate beyond the geologic record whether subsequent evolutionary stages lead to the evolution of intelligent behavior, we turn to the exploration of our solar system. In order to investigate, in the short term, whether the evolution of life is subject to convergence throughout the cosmos, we have at least two possibilities. First, we can directly test whether evolution of intelligent behavior has followed a convergent evolutionary pathway elsewhere in the universe by means of the Search for Extraterrestrial Intelligence (SETI) project (Ekers et al., 2002). Unfortunately, no definite signal that could be interpreted as originating from an advanced civilization has ever been detected.

A second alternative, although much more restricted in scope, is currently in progress. We can test for the possible existence of the lowest stages of the evolutionary pathway

within the solar system, namely at the level of microorganisms. One approach is currently being carried out in terms of the search for life on Mars. Another approach, still within the solar system, is to search in due course for life on the Jovian satellite Europa (Chela-Flores, 2003: 307-12; 2006, in press). Even beyond our solar system, scientific research may help us to decide whether environments exist that fulfill conditions favorable to life's origin and evolution. This is due in part to the fact that we are aware of multiple examples of solar systems. In addition, we suppose that stable conditions persist in extrasolar planets. By stable conditions, it should be understood that the planet (or satellite), where life may evolve, is bound to a long-lived star. In other words, the time available for the origin and evolution of life should be sufficient to allow life itself to evolve, before the solar system of the host planet or satellite reaches the final stages of stellar evolution, such as at the red-giant and supernova phases.

It is also assumed that major collisions of large meteorites with a habitable world are infrequent after the solar system has passed through its early period of formation. Under such stable conditions, the gradual action of natural selection would be expected to be the dominant mechanism in evolution. Fortunately, the existence of stable earth-like planetary conditions is an empirical question for which we will be able to give partial answers in the foreseeable future. Reliable observational techniques are currently being provided to image Jupiter-like planets orbiting at several astronomical units from their corresponding stars. Hence, we may conclude that in the not-too-distant future we will be able to address the following question on the evolution of intelligent behavior: Is the evolution of the cosmos "fine-tuned" for the inevitable emergence of intelligent behavior throughout the cosmos? The assumed universality of biological evolution suggests a

positive answer to this question, provided that stable planetary conditions are maintained in a given planet, or satellite, over geologic time.

A third factor in favor of the inevitability of the evolution of intelligent behavior in the cosmos is natural selection, which seems to be powerful enough to shape terrestrial organisms to similar ends, independent of historical contingency. Likewise, in view of the assumed universality of biology, we would expect evolutionary processes to take place in the cosmos that are mechanistically similar to those that have driven the evolution of life on earth. I will discuss some examples that support this view. Before approaching the question of convergent evolution, however, we should first recall that the set of factors influencing the relative degree to which earth's biota has been shaped is still a debatable topic. According to the hypothesis of universal Darwinism, life on earth, and possibly elsewhere, may have been shaped either by contingency or by the gradual action of natural selection. It may be possible to document convincingly whether, independent of historical contingency, natural selection is powerful enough for organisms living in similar environments to be shaped to similar ends. For this reason, I highlight the following examples, which suggest that, to a certain extent and in certain conditions, natural selection may be stronger than chance:

- Black European fruit flies (*Drosophila subobscura*) were transported to California more than twenty years ago. This event has provided the possibility of testing the role of natural selection in two different continental environments. Pacific coast *D. subobscura* (from Santa Barbara to Vancouver) were compared in wing-length with European specimens (from Southern Spain to the middle of Denmark). After

half a dozen generations living in similar conditions, the increase in wing length was almost identical (four percent). This is a compelling case in favor of the key role played by natural selection in evolution (Huey et al., 2000: 308-09).

- Anole lizards from some Caribbean islands (*Anolis spp.*) provide another example of evolutionary convergence. In Cuba, Hispaniola (shared by Haiti and the Dominican Republic), Jamaica, and Puerto Rico (the so-called Greater Antilles), the observed phenomenon suggests that in similar environments adaptive radiation can overcome historical contingencies to produce strikingly similar evolutionary outcomes. We could even say that *replicated adaptive radiation* has occurred in the various islands. In fact, it has been shown that although many species were known to thrive on these islands, some groups of lizards from different islands living in similar environments also look similar (Losos et al., 1998: 2115-18). Genetic analysis has shown that similar traits have evolved in distantly related species for coping with similar environments (such as treetops or ground-dwellings): Anoles that live on the ground have long, strong hind legs, while those living at treetops have large toe-pads and short legs. Repeated evolution of similar groups of species (both morphologically and ecologically) suggests that adaptation is responsible for the predictable evolutionary responses of the anole lizards of the Caribbean. Indeed, we can speak in this case of evolutionary history repeating itself (Vogel, 1998: 2043).

Finally, in order to decide whether the standard laws of physics and biology imply the evolution of intelligent behavior, it is instructive to appreciate the implications of the

existence of several *constraints on chance*. These constraints are relevant to the question of whether life elsewhere might follow pathways analogous to the ones it has already followed in terrestrial evolution. Christian de Duve has enumerated various examples of constraints on chance (de Duve, 1995: 296-97; 2002; and this volume):

- Not all genes are equally significant targets for evolution. The genes involved in significant evolutionary steps are few in number; these are the so-called regulatory genes. In these cases, mutations may be deleterious and consequently are not fixed.

- Once a given evolutionary change has been retained by natural selection, future changes are severely constrained; for example, once a multicellular body plan has been introduced, future changes are not totally random, as the viability of the organisms narrows down the possibilities. For instance, once the body plan of mammals has been adopted, mutations such as those that are observed in *Drosophila*, which exchange major parts of their body, are excluded. Such fruit-fly mutations are impossible in the more advanced mammalian body plan.

- Not every genetic change retained by natural selection is equally decisive. Some may tend to increase biodiversity rather than contribute to a significant change in the course of evolution.

Implicit in Darwin's work is chance represented by the randomness of mutations in the genetic patrimony and their necessary filtering by natural selection. However, the novel

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point of view that astrobiology forces on us is to accept that randomness is built into the fabric of the living process. Yet, contingency, which is represented by the large number of possibilities for evolutionary pathways, is limited by a series of constraints.

Natural selection necessarily seeks solutions for the adaptation of evolving organisms to a relatively limited number of possible environments. From cosmochemistry we know that the elements used by the macromolecules of life are ubiquitous in the cosmos.

To sum up, a finite number of environments force a limited number of options on natural selection for the evolution of organisms. We expect convergent evolution to occur repeatedly, wherever life arises. Consequently, it makes sense to search for the analogs of the attributes that we have learned to recognize on earth, especially the evolution of intelligent behavior.

Conclusion

Data from the current fleet of space probes that are capable of searching for signs of life in the solar system suggest that extraterrestrial life could be identified sometime in the near future. Thus, if we can settle the question of the occurrence of a Second Genesis elsewhere in the universe, additional information would be available to discuss the question of fine-tuning in biochemistry. Earlier, I extended the meaning of convergence from biology to the space sciences in an effort to provide a solid scientific basis for the concept that the universe is fit for the origin and evolution of life.

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Closely related to the issue of extending convergence from the life to the space sciences is the subject of the intelligibility of life in the universe, a significant topic that requires an explanation. In this chapter, two aspects of the intelligibility of life in the universe were discussed in scientific terms, namely, the origin and the evolution of intelligent behavior in the universe. The arguments were centered on whether evolution is dominated by either contingency, or by the gradual action of natural selection. Random gene changes accumulating over time may imply that the course of evolution is generally unpredictable, but constraints on chance, as argued above, put some powerful bounds on the degree of uncertainty.

Other contingent factors are the extinction of species due to asteroid collisions or other calamities, although these uncertainties may affect only the evolution of single lineages. However, such questions are of lesser interest to the larger issues that are relevant to either natural theology, or to science. This is particularly true when the question of fine-tuning is raised in physics, or biochemistry—that is, whether the appearance of biological features such as vision, locomotion, nervous systems, brains, and intelligent behavior is inevitable, rather than the preservation of a given species. I have further argued throughout this chapter that contingency does not contradict a certain repetition of natural history. Evolution allows a certain degree of predictability of the eventual biological properties that are likely to evolve, mainly because of convergence in the life sciences, but especially, as we have stressed repeatedly, because of the useful new concept of convergence in the space sciences.

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