LIFE BEFORE ITS ORIGIN ON EARTH: IMPLICATIONS OF A LATE EMERGENCE OF TERRESTRIAL LIFE

Julian Chela-Flores*,†
*The Abdus Salam ICTP, Trieste, Italy
†IDEA, Caracas, Venezuela

CHAPTER OUTLINE

1 INTRODUCTION

The established view that life on Earth is represented by a single-rooted phylogenetic tree with three domains (Woese et al., 1990) is confronted by alternative scenarios that view life in the cosmos, not as a tree of life, but better described by the metaphor of a universe with a "cosmic forest of life" (cf., Section 3). We attempt to follow-up the possibility that life on Earth is a relatively recent phenomenon in geologic terms. There have been some suggestions that this may be the case, for instance,

Habitability of the Universe Before Earth, editors: Richard Gordon & Alexei Sharov, Volume 1 in the series: Astrobiology: Exploring Life on Earth and Beyond, series editors: Pabulo Henrique Rampelotto, Joseph Seckbach & Richard Gordon. ISSN 2468-6352. https://doi.org/10.1016/B978-0-12-811940-2.00015-0

Lineweaver (2001) has supported this view with his estimate on the age distribution of terrestrial planets in the Milky Way. His calculations show that Earth-like planets began forming more than 9.2 billion years ago and that their median age is $t_{med} = (6.4 \pm 0.9) \times 10^9$ years. This estimate is much greater than the age of the Solar System itself.

Living phenomena that emerged prior to terrestrial life has been suggested implicitly, though it has only been clearly stated in fiction. For example, Carl Sagan, a distinguished astronomer, astrobiologist, and confirmed enthusiast for science communication, militated in favor of life elsewhere being more ancient than life on Earth: This opinion is evident in his novel Cosmos. After a first contact had been made with another intelligent species, the more evolved beings assert (Sagan, 1985):

> In our case, we emerged a long time ago on many different worlds in the Milky Way. The first of us developed interstellar space-flight.

In the same context, the English writer, Sir Arthur C. Clarke, remarkable for his writings on science fiction and his vision on the progress of science, advocated that life on Earth was a late cosmic phenomenon. This is especially clear in the short story The Sentinel (Clarke, 1951): "When our world was half its present age, something from the stars swept through the Solar System. . . and went again upon its way."

In terms of a traditional scientific approach that is more appropriate for the present work, theoretical hypotheses have only gone as far as arguing in favor of terrestrial life being a rare case in a galactic scale (Carter, 1983). Additional theoretical discussions support the rare life hypothesis, but accept that the "final scientific assessment on life in the universe will only come from biologists and observers" (Livio, 2008).

The question of how ancient life in the cosmos really emerged can be tested, in principle, with present instrumentation and with future feasible technologies that are now being developed. These open questions force us to reconsider life before its origin on Earth. Some implications of the existence of extraterrestrial life as an astrobiology phenomenon have been covered in the cases of theology (Haught, 1998; Lovin, 2015) and philosophy (Lupisella, 2015).

1.1 TIME AVAILABLE BEFORE THE EMERGENCE OF LIFE ON EARTH

The age of the Solar System is about half the age of our galaxy. But the Sun itself is about half way through its lifetime. Consistent with past estimates, Earth was formed after 80% of Earth-like planets already existed (Behroozi & Peeples, 2015). Hence, the time available for life to have evolved before Earth is considerable.

The afterglow radiation of the cosmic microwave background (CMB) has steadily decreased in temperature as the universe expands. Today, the expansion has induced a CMB temperature close to the absolute zero. This is equivalent to a red shift of $z \sim 100$. Yet going back in time, we can estimate the time after the Big Bang as being 15 Myr when the temperature was close to room temperature, a condition that is favorable to life (Loeb, 2014). The implication is that in such circumstances any planet, or satellite around an early star, could have sustained oceans of liquid water.

This phenomenon would be independent of the particular orbit, and it may even happen on planets that have escaped from their original stellar orbit. The only question that remains open is whether the early star system would have generated sufficient basic chemical elements (produced from earlier supernovae) for supporting biosynthesis. In the absence of sufficient data, such an early onset of life in the cosmos remains an open possibility.

Thermal gradients are needed for life. These can be supplied by geological variations on the surface of rocky planets. Examples for sources of free energy are geothermal energy powered by the planet's gravitational energy at the time of its formation and radioactive energy from unstable elements produced by the earliest supernova. These internal heat sources (in addition to possible heating by a nearby star) may have kept planets warm even without the CMB, extending the habitable epoch from such an early age to later times.

The CMB temperature at a time well before the moment of cosmic decoupling may have allowed ice to form on objects that delivered water to a planet's surface. This phenomenon may have helped to maintain the cold trap of water in the planet's stratosphere. Planets could have kept a blanket of molecular hydrogen that maintained their warmth (Stevenson, 1999; Pierrehumbert & Gaidos, 2011), allowing life to persist on internally warmed planets at late cosmic times. If life persisted at $z \sim 100$, it could have been transported to newly formed objects through panspermia (McNichol & Gordon, 2012). Under the assumption that interstellar panspermia is plausible, the redshift of $z \sim 100$ can be regarded as the earliest cosmic epoch after which life was possible in our Universe. Searching for atmospheric biomarkers in planets, or satellites around low-metallicity stars in the Milky Way galaxy, or its dwarf galaxy satellites can test the feasibility of life in the early universe. Such stars represent the closest analogs to the first generation of stars at early cosmic times.

1.2 RATIONALIZING OUR ORIGINS IN TERMS OF THERMODYNAMICS

A recent original approach to the origin of life is due to Jeremy England, which applies to any terrestrial-like planet. He emphasizes rationalization of the origin of life in terms of thermodynamics (England, 2013), rather than on chemical evolution, as we have persevered exhaustively in the past (Ponnamperuma & Chela-Flores, 1995; Chela-Flores et al., 1995, 2001). We assume only the occurrence of biological phenomena that are independent of any contingent facts here on Earth. We further assume that such conditions may hold in other places, such as in exoplanets, where life might develop, since the expected number of Earth-like planets is sufficiently large (cf., Section 1.1). We will refer to certain biological phenomena that make no reference to any contingent facts here on Earth. In addition, such special conditions could be expected to hold in other places where life might develop. As a consequence of the two previous assumptions, universal biology may be a robust hypothesis (Mariscal, 2015).

To a certain extent, such an insight into a universal biology may be testable, especially concerning the case of evolutionary convergence (Chela-Flores, 2003). This is in principle possible to test in the foreseeable future, due to the approval of funding by the European Space Agency (ESA) for a mission to the Jovian icy satellites in the 2020s (Grasset et al., 2013). Another factor in favor of testing convergence is the formidable progress in instrument miniaturization that has already an appreciable heritage in previous successful exploration of the Solar System (Tulej et al., 2015). These two factors facilitate the search for feasible biomarkers that we have repeatedly suggested in the past (Chela-Flores & Kumar, 2008; Chela-Flores et al., 2015).

2 HOW WOULD WE SEE OURSELVES IF EARLY ORIGINS ARE IDENTIFIED?

Biocentrism is the view adopted by some philosophers and scientists that life has evolved exclusively on Earth. This has been a concept deeply rooted into our cultural history. Since the ancient times of Greek civilization, it has persevered to relatively recent times (Henderson, 1913; Chela-Flores, 2005).

It has been reconsidered, firstly by the astronomy of Copernicus and Galileo that displaced our planet from the center of the cosmos. With Darwin, we reevaluated biocentrism once more.

2.1 APPROACHING THE END OF BIOCENTRISM IF LIFE ON EARTH IS A LATECOMER

The displacement of humans took place from a privileged position that otherwise would have been radically removed from the evolution of life on Earth. Now, Darwinism is widely accepted, even in a theological context. We should now turn to the restricted topic of cultural implications that detection of an extraterrestrial civilization, either contemporary, but especially preceding us, might have on the ever-receding position of biocentrism.

Two different cases are relevant for the theme of life emerging in the universe. One aspect concerns firstly, whether the origin of the extraterrestrial civilization is contemporary or less developed than ours, or secondly, whether there are further implications if life on Earth is a latecomer in the evolution of life in the cosmos.

2.2 ANTHROPOCENTRISM

This doctrine maintains that man is the center of everything, the ultimate end of nature. But there are topics that argue in favor of a wider point of view. One is the surprising evolution of brain size in humans; for the knowledge we have today is very narrow when viewed in geologic time. Recently, in these terms dolphins on Earth had brains that were comparable with our ancestors (Marino, 2000), but more surprisingly, dolphin EQ actually exceeded the EQ of our ancestors for times greater than 2 Mya.

This is relevant to the evolution of intelligence, including human intelligence, many aspects of which may not be exceptional. Lori's findings have important implications for the probability of the emergence of human level of intelligence in an independent lineage. In the case of an early evolution of life elsewhere, the evolution of intelligence comparable to our experience on Earth is not excluded and anthropocentrism recedes as a valid doctrine.

The second point to keep in mind is by the Australian ethicist Peter Singer (Singer, 1993), who has argued that the implications of the fundamental principle of equality for humans should not be seen from the limited point of view of anthropocentrism and equality should be extended to animals as well. But, once again if life on Earth is a latecomer, the Singer extrapolations should be extended to all life, independent of both their evolutionary stage and their cosmic location.

3 PHILOSOPHICAL COMMENTS ON AN EARLY "FOREST OF LIFE"

The metaphor of a "cosmic forest of life" (Martini & Chela-Flores, 1999) is a convenient phrase that summarizes the possibility that life exists on the large number of exoplanets discovered by the Kepler mission. From early philosophical doctrines, beginning with the Greek philosopher Protagoras (born around 500 BC, in Abdera), there has been the conviction that "man is the measure of all things" (Russell, 1991). Sadly, this has still not been removed from our thinking when we search for life in cosmos.

3.1 PROCESS PHILOSOPHY

Process philosophy holds that what exists in nature is not just originated and sustained by processes, but in fact processes specify what exists. Similarly, process theology is an approach to natural theology based on the metaphysics of Alfred North Whitehead, who rejects Divine Action in terms of causality, especially regarding events that are mostly determined by their past. This philosophical system is considered to be particularly helpful in the task of constructing an evolutionary theology that may throw some further insights into Darwinism (Haught, 1998) and consequently into astrobiology.

Another approach along these lines points out that theologians already have the concept of Divine action continuous creation, which can be used to explore the implications of modern science for religious belief (Coyne, 2005). In this view, God is working with the universe (and consequently, life in the cosmos). The universe has a certain vitality of its own like a child does. It has the ability to respond to words of endearment and encouragement. You may discipline a child, but you try to preserve and enrich the individual character of the child and its own passion for life. A parent must allow the child to grow into adulthood, to come to make its own choices, to go on its own way in life.

In such a way, we can imagine that Divine action may deal with the universe and its life contents. There are no compulsory theological arguments pointing towards a limit, in this sense, to single out a planet in the periphery of a single galaxy such as ours. Along the above lines, it is possible that evolution may also provide a way in which the tradition of natural theology may undergo a renewal. Within the scope of process philosophy, instead of discussing design without a designer, such as in terms of Darwinism (Ayala, 1998), both a renewed philosophy and a revived natural theology may take place if we interpret correctly the origin, evolution, and distribution of life (astrobiology).

3.2 STELLAR EVOLUTION

Stellar evolution predicts that the lifetime of the Sun will continue for a few billion years, while the science of anthropology suggests that humans are a fairly recent addition to an Earth biota, whose origins may be traced back to microorganisms that emerged on the early Earth from 3 to 4 billion years ago. We expect that philosophers and theologians will continue their independent search for a deeper understanding.

Science will be confronted with ever-increasing mysteries, as our scientific instruments become better and more accurate to allow confrontation of theory with experiment. The questions of how the universe and life in it were formed will reveal new insights. Some questions, however, escape the scope of astrobiology. We expect that future developments in philosophy and theology will gradually give us better insights into the question that was raised by the philosopher Gottfried Wilhelm Leibniz (1714):

> Why is there something rather than nothing?. . ..

Further, assuming that things must exist, it must be possible to give a reason why they should exist as they do and not otherwise. Would the presence of a cosmic forest of life guide us towards a partial answer to Leibnitz queries?

3.3 CULTURAL COMMENTS ON AN EARLY FOREST OF LIFE

With the eventual discovery of other life in the cosmos, either contemporary or before the Sun was formed, we would have a deeper understanding of human beings. Such an event would lead to a careful reappraisal of the above biblical quotation. In order to find out what is the position of our tree of life in the universe, we have to appeal to astrobiology. Evolutionary convergence is an aspect of the evolutionary phenomenon that constrains its randomness. In his book, Chance and Necessity Monod put too much emphasis on the role played by pure randomness in Darwinism (Monod, 1972).

Inserting the word "blindness" in this context is, according to Polkinghorne (1996), a tendentious adjective. He has exposed the limitation of this point of view: It could be interpreted that a world of chance and necessity is necessarily one that lacks purpose. Alternatively, although it is possible to defend such a metaphysical statement, "it is a claim that should not be presented as if it were a scientific conclusion."

The possibility that evolutionary convergence has actually taken place elsewhere in the universe is a question that can also be tested observationally by means of radio astronomy (cf., Section 1.2 in relation with testing the restricted aspect of universal biology in the Solar System). Since the middle of the last century, signals have been searched from evolutionary processes that have actually led to intelligence in the sense of beings that have actually developed communication technologies. The question still remains open, but this astronomical search would be a direct way to get profound insights into the question raised in the title of this chapter. The search for other intelligences assumes that the tendencies of terrestrial biological evolution (towards more complex neural networks such as our brains) with the consequent intelligences, if eventually successful, could serve as a first stage in our search for the place of our tree of life in the universe.

4 TERRESTRIAL LIFE AS A LATECOMER IN COSMIC EVOLUTION

To conclude, in this section we discuss what would be the cultural changes that would be forced upon us if terrestrial life were a latecomer in cosmic evolution. From the point of view of the present work, we focus, firstly, on what were the impressions of the presence of life on Earth in the middle of the 20th century, well-summarized by the English philosopher Bertrand Russell (1985). Secondly, we will review the cultural perspectives in the foreseeable future, now that new insights are open due to the existence of planetary systems around other stars. This additional information will be possible by probing exoplanets in the next few years, after the completion of better, much improved astronomical instrumentation that will go beyond the Kepler mission.

The Earth is one of the smaller planets of a not particularly important star, a very minor portion of the Milky Way, which is one of the very large number of galaxies. This is still a fair description of our position in the cosmos. Russell continues with a stronger statement that there might be no life at all except on this planet or now in agreement with the "rare Earth" hypothesis that the origin of life and the evolution of biological complexity on Earth (and, subsequently, human intelligence) required an improbable combination of astrophysical and geological events and circumstances (Ward & Brownlee, 2000).

Quite impressively for a writer in the middle of the 20th century, Russell continues to consider the possibility of extra-solar planets "in such stages of development this one," but from the point of view of this work, we disagree with his anticipation of the existence being confined to few parts of the universe.

For several years, the American agency, NASA, sponsored the Kepler mission with a satellite in a solar orbit similar to the terrestrial one. With the Kepler results, there is now a growing conviction among astrobiologists for the existence of life in the two thousand, or so, planets known to be orbiting around other stars. Several of these are Earth-like. In the coming years, among the components of this restricted group, we are convinced that they will provide examples, firstly of a second genesis with a second tree of life, and secondly, evidence would be forthcoming for a full forest of life. The scientific basis for this conviction is the imminent arrival of various instruments that are now under construction, including new huge telescopes. But life as a latecomer in evolution raises new questions beyond Russell's impressive foresight that was limited by his early approach. We discuss in turn the two cases of the solar system and other solar systems.

There is some preliminary conviction among astrobiologists that at least in the solar system, there may have been two trees of life in the cosmic forest of life and the terrestrial tree may have been preceded by one on Mars: Firstly, we survived here on Earth. But on Mars, there is ample evidence that bacterial life may have started off contemporarily with the emergence of our own bacteria some 4 billion years ago. Yet, our dynamic planet with earthquakes and atmosphere worked in favor of preserving bacterial life. These aspects of the terrestrial geophysics allowed Darwinian evolution to raise the bacterial blueprint to the human one. But Mars lacked (and still lacks) the life-friendly dynamic features of our planet. It gave no opportunity for evolution to raise the bacterial blueprint, inevitably leading to the extinction of Martian life that most likely emerged only as an episode early in the solar system.

Yet, we still cannot exclude extant microbial life under the polar ice or in underground sites. Others have discussed the possibility that the possible episodic biological event may have preceded the terrestrial one (Davies, 1998). If it did happen, that event would encourage further theological discussions beyond the literal interpretation of Genesis. In the Leibnitz quotation (cf., Section 3), it would be possible to give a reason why things should exist as they do, and not otherwise. This question of existence can be appreciated in a different light if we were latecomers in the universe.

Granted the hypothesis of life being a latecomer in cosmic evolution, philosophy would have a fresh point of view to face the Leibnitz queries. Indeed, astrobiology would provide an explanation why life would exist on Earth, especially if the above-mentioned general thermodynamic rationalization is valid. In this case, life would be the inevitable outcome on Earth-like planets in a process that would be traced back to planetary formation in earlier cycles of life. Philosophy would be presented with the new challenge for the interpretation of why the living process should exist as it does, and not otherwise.

5 CONCLUSION

New cultural perspectives will arise in the post-Kepler era, when we would be facing the eventual recognition of a multitude of terrestrial-like worlds in our galaxy and beyond. The likelihood of the emergence of habitable planets, before the emergence of the Solar planetary system, is now a possibility that deserves consideration, given the forthcoming short-term development of improved astronomical instrumentation that will clarify what are the specific biomarkers that would be recognizable. We feel that the above sketch of the cultural novelty in Section 4 deserves more thorough attention, beyond the preliminary comments of the present work.

REFERENCES

Ayala, F.J., 1998. Darwin's devolution: design without designer. In: Russell, R.J., Stoeger, W.R., Ayala, F.J. (Eds.), Evolutionary and Molecular Biology: Scientific Perspectives on Divine Action. Vatican Observatory and the Center for Theology and the Natural Sciences (CTNS), Vatican City State/Berkeley, CA, pp. 101–116.

Behroozi, P.S., Peeples, M., 2015. On The History and Future of Cosmic Planet Formation. MNRAS 454, 1811–1817.

Carter, B., 1983. The Anthropic Principle and its Implications for Biological Evolution. Phil. Trans. R. Soc. Lond. A 310, 347.
Chela-Flores, J., 2003. Testing evolutionary convergence on Europa. Int. J. Astrobiol. 2 (4), 307–312.
Chela-Flores, J., 2005. Fitness of the universe for a second genesis: is it compatible with science and Christianity? Sci. Christ. Belief 17 (2), 187–197.
Chela-Flores, J., Kumar, N., 2008. Returning to Europa: can traces of surficial life be detected? Int. J. Astrobiol. 7, 263–269.
Chela-Flores, J., Chadha, M., Negron-Mendoza, A., Oshima, T. (Eds.), 1995. In: Chemical Evolution: Self-Organization of the Macromolecules of Life (A Cyril Ponnamperuma Festschrift), Vol. 139. A. Deepak Publishing, Hampton, VA.
Chela-Flores, J., Owen, T., Raulin, F. (Eds.), 2001. The First Steps of Life in the Universe. Kluwer Academic Publishers, Dordrecht, The Netherlands.
Chela-Flores, J., Cicuttin, A., Crespo, M.L., Tuniz, C., 2015. Biogeochemical fingerprints of life: earlier analogies with polar ecosystems suggest feasible instrumentation for probing the Galilean moons. Int. J. Astrobiol. 14, 427–434. http://users.ictp.it/~chelaf/IJA2015.pdf.
Clarke, A. C., 1951. The Sentinel. Reprinted in: 2001 A Space Odyssey. Arrow Books, 1988, pp. 239–250.
Coyne, S.J.G., 2005. God's chance creation. Tablet 6. http://www.ictp.it/~chelaf/Coyne.pdf.
Davies, P.C.W., 1998. Did Earthlife come from Mars? In: Chela-Flores, J., Raulin, F. (Eds.), Exobiology: Matter, Energy, and Information in the Origin and Evolution of life in the Universe. Kluwer Academic Publishers, The Netherlands, pp. 241–244.
England, J.L., 2013. Statistical physics of self-replication. J. Chem. Phys. 139, 121923-1–121923-8.
Grasset, O., Dougherty, M.K., Coustenis, A., Bunce, E.J., Erd, C., Titov, D., Blanc, M., Coates, A., Drossart, P., Fletcher, L.N., Hussmann, H., Jaumann, R., Krupp, N., Lebreton, J.-P., Prieto-Ballesteros, O., Tortora, P., Tosi, F., Van Hoolst, T., 2013. JUpiter ICy moons Explorer (JUICE): an ESA mission to orbit Ganymede and to characterize the Jupiter system. Planet. Space Sci. 78, 1–21.
Haught, J.F., 1998. Darwin's gift to theology. In: Russell, R.J., Stoeger, W.R., Ayala, F.J. (Eds.), Evolutionary and Molecular Biology: Scientific Perspectives on Divine Action. Vatican Observatory and the Center for Theology and the Natural Sciences (CTNS), Vatican City State/Berkeley, CA, pp. 393–418.
Henderson, L.J., 1913. The Fitness of the Environment: An Inquiry into the Biological Significance of the Properties of Matter. MacMillan, New York. Reprinted in 1958 by Beacon Press, Boston, 1970.
Leibniz, G., 1714. The principles of nature and grace, based on reason. In: Loemker, L. (Ed.), Philosophical Papers and Letters. D. Reidel, Dordrecht, pp. 636–642. 1969.
Lineweaver, C.H., 2001. An estimate of the age distribution of terrestrial planets in the Universe: quantifying metallicity as a selection effect. Icarus 151, 307–313.
Livio, M., 2008. The interconnections between cosmology and life. In: Barrow, J.D., Conway Morris, S., Freeland, S.J., Harper Jr., C.L. (Eds.), Fitness of the Cosmos for Life Biochemistry and Fine-Tuning. Cambridge University Press, Cambridge, pp. 114–131.
Loeb, A., 2014. The habitable epoch of the early Universe. Int. J. Astrobiology 13 (4), 337–339.
Lovin, R.W., 2015. Astrobiology and theology. In: Dick, S.J. (Ed.), The Impact of Discovering Life Beyond Earth. Cambridge University Press, Cambridge, pp. 222–232.
Lupisella, M., 2015. Life, intelligence and the pursuit of value in cosmic evolution. In: Dick, S.J. (Ed.), The Impact of Discovering Life Beyond Earth. Cambridge University Press, Cambridge, pp. 159–174.
Marino, L., 2000. Turning the empirical corner on Fi. In: Bioastronomy 99 A New Era in Bioastronomy, Astronomical Society of the Pacific Conference Series, pp. 431–435.
Mariscal, C., 2015. Universal biology: assessing universality. In: Dick, S.J. (Ed.), The Impact of Discovering Life Beyond Earth. Cambridge University Press, Cambridge, pp. 113–126.
Martini, C.M., Chela-Flores, J., 1999. Dialogo. In: Sindoni, E., Sinigaglia, C. (Eds.), Carlo Maria Martini Orizzonti e limiti della scienza (Decima Cattedra di non credenti). "Scienze e Idee," Directed by G. Giorello, Raffaello Cortina Editore, Milano, pp. 65–68.

McNichol, J., Gordon, R., 2012. Are we from outer space? A critical review of the Panspermia hypothesis. In: Seckbach, J. (Ed.), Genesis—In the Beginning: Precursors of Life, Chemical Models and Early Biological Evolution. Springer, Dordrecht, pp. 591–620.

Monod, J., 1972. Chance and Necessity. Collins, London. p. 187.

Pierrehumbert, R., Gaidos, E., 2011. Hydrogen greenhouse planets beyond the habitable zone. Astrophys. J. Lett. 734, 1–5. https://doi.org/10.1088/2041-8205/734/1/L13.

Polkinghorne, J., 1996. Scientists as Theologians. SPCK, London.

Ponnamperuma, C., Chela-Flores, J. (Eds.), 1995. Chemical Evolution: The Structure and Model of the First Cell. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Russell, B., 1985. The existence and nature of God. In: Rampel, R., Brink, A., Moran, M. (Eds.), Collected Papers of Bertrand Russell, vol. 12. Allen and Unwin, London. Reproduced in: Greenspan, L., Andersson, S. (Eds.) (1999). Russell on Religion. Selections from the writings of Bertrand Russell, Routledge, London and New York, pp. 92–106.

Russell, B., 1991. History of Western Philosophy and its Connection with Political and Social Circumstances from the Earliest Times to the Present Day. Routledge, London. pp. 91–97.

Sagan, C., 1985. Contact. Pocket Books, a division of Simon & Schuster Inc., New York. (Chapter 20), p. 366.

Singer, P., 1993. Practical Ethics, second ed. CUP, Cambridge.

Stevenson, D.J., 1999. Life sustaining planets in interstellar space? Nature 400, 32–33.

Tulej, M., Neubeck, A., Ivarsson, M., Riedo, A., Neuland, M.B., Meyer, S., Wurz, P., 2015. Chemical composition of micrometer-sized filaments in an Aragonite host by a miniature laser-ablation/ionization mass spectrometer. Astrobiology 15 (8), 1–14.

Ward, P., Brownlee, D., 2000. Rare Earth: Why Complex Life is Uncommon in the Universe. Springer, New York.

Woese, C.R., Kandler, O., Wheelis, M., 1990. Towards a natural system of organisms: proposal for the domains Archaea, Bacteria, and Eucarya. Proc. Natl. Acad. Sci. U.S.A. 87 (12), 4576–4579.

FURTHER READING

John Paul II., 1992. Discorso di Giovanni Paolo alla Pontificia Academia delle Scienze. L'Osservatotre Romano, 1 Novembre, p. 8.