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Where Do We Go from Here? *Astrobiology* Editorial Board Opinions

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The James Webb Space Telescope is slated for launch in 2018. Working primarily in the infrared, the James Webb will search for the first bright objects of the early Universe, examine how galaxies evolve, study the birth and development of stars, and investigate the physical properties of star systems as they relate to the building blocks of life. An international collaboration between NASA, ESA, and CSA, the James Webb Space Telescope along with upcoming missions such as ESA's Characterizing Exoplanet Satellite (CHEOPS) and NASA's OSIRIS-Rex asteroid sample-return mission will offer investigators data and perhaps some answers as to how the Universe began, how it evolved, and how life occurred on Earth or elsewhere.

By the mid-21st century, the James Webb Space Telescope will have reached its working lifetime. Innumerable astrobiologically driven space missions will have been flown and completed, and the exact mechanisms that contribute to the origin of life as we know it will likely not be fully understood. But that isn't to say we will have learned little between now and then. To the contrary, given the groundwork already in place—our investigations into the chemistry of life, the evolution of the Solar System and the planets, the occurrence of exosolar systems and exoplanets—research efforts yet to be realized, whether by way of the James Webb or other missions of merit, will surely move the discipline of astrobiology ever closer to understanding how something as enigmatic as life has come into its own over the course of some 14 billion years.

In an effort to learn more about what working astrobiologists believe are the most pressing issues in the search for, and understanding of, life in the Universe, we asked members of our editorial board six questions that strike at the heart of where, as astrobiologists, we go from here.

In the responses below, I think you will find that those who are at the forefront of astrobiology not only have a firm understanding of where we've been and where we are now but also where, in this Universe, we carry on in the search for life.

—Lawrence Cady, Managing Editor

Given recent advances in exoplanet research, what is the likelihood that our first discovery of life beyond the confines of Earth will be the result of exoplanet or exomoon investigation?

André Brack

The goal of exoplanet investigation is twofold: to discover habitable exoplanets and to demonstrate that they are inhabited by living species. Inspired by terrestrial life, it is generally believed that any extraterrestrial life must have emerged from the processing of reduced organic molecules by liquid water (Brack *et al.,* 2010). This is not just an anthropocentric point of view: the basic ingredients of terrestrial life, reduced carbon-based molecules, and liquid water have very specific properties demonstrated in the laboratory (Brack, 2001, 2007a, 2010). Therefore, liquid water is considered to be one of the prerequisites for life in that it would have to be present on a terrestrial planet for life to occur. Life is autocatalytic in essence and must have the capacity to evolve. To evolve, that is, to improve the efficiency of self-reproduction and increase its diversity, the molecules that bear hereditary memory must be able to reach a certain degree of complexity. This can be best achieved with a scaffolding of polyvalent atoms. In chemists' hands, carbon chemistry is very productive in this respect. Carbon chemistry is universal, since about 110 carbon-containing molecules, up to $HC_{10}CN$, have been identified in the interstellar medium, while water molecules are the most abundant heteroatomic molecules.

Among the 2000 or so exoplanets discovered so far, 20 super Earths are considered as habitable (http://phl.upr.edu/projects/habitable-exoplanets-catalog). Chemistry is reproducible: the same starting conditions must produce the same results. The question is now to approach the complexity of the starting conditions. The planet Earth has at least two early specificities: a satellite and the neighborhood of an asteroid belt (plate tectonics only started to become prevalent around about 3.2 Ga, and we don't know when the magnetic field was initiated). It is quite impossible to know today whether all or some of these specificities were required. The members of a small Amazonian tribe count *one, two, many*. We are eagerly looking for the first exolife to be able to claim *one, two, everywhere,* to draw terrestrial life out of its cosmic solitude.

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Jorge E. Bueno Prieto

The likelihood is high, although limited, because the discovery of exoplanets is not enough to guarantee the existence of life on any of them. Though to date we have discovered more than 1700 planets orbiting around stars different from the Sun, those that can provide the conditions for life as we know it are few and offer a minimum scope of possibilities.

We know that a more detailed study of any of those exoplanets is a great challenge for astrobiology because of how limited our technological resources are to describe the surface aspects and the diverse favorable interactions for the development of life, at least in its basic form.

With the use of detection techniques, the type of extrasolar system, its orbits, its moons, and the atmospheric and surface conformation have been described; but internal mechanisms that lead to proving the presence of any form of life in any phase of the planet or moon have not been possible, and this can only be achieved through work and inspections as is being done in Mars.

Among the group of exoplanets, super Earths are highlighted. They are planets with conditions similar to those of Earth, but with a mass range 1–20 times the mass of Earth, which offer the highest potential to develop life due to their size and our ability to detect life through our technology.

The study of extrasolar planets may help us partially understand questions about the formation of our Solar System, the different types of planets, and the atmospheric and geological conformations that may have conditioned the appearance of life on Earth and, thus, on another planet or moon. However, it is wise to understand that the possibility of an extrasolar planet providing answers to our Solar System is limited.

Charles Cockell

Without definitive knowledge of the probability that habitable conditions give rise to an origin of life, it is impossible to place any estimate on the likelihood of life beyond the confines of Earth. Nevertheless, in the absence of biosignatures of life readily detectable in the near surface of locations such as Mars or icy moons of the Solar System, it is possible to imagine a hypothetical scenario where a biosignature is detected beyond our Solar System before we are able to achieve the enormously challenging task of deep drilling into the subsurface of bodies in our own Solar System. However, the chronological order of potential discovery is less important than the fact that exoplanet research allows for the study of a sample size of planetary bodies many orders of magnitude greater than the number in our solar system, whilst avoiding the possibility that the discovery of life elsewhere in our Solar System is an example of experimental pseudo-replication, even if its origin is independent of Earth.

As all the major planetary bodies in our Solar System came from the same protoplanetary disc, we could never be sure that multiple origins of life were not the result of an extremely rare chemical anomaly in our disc. They are not statistically independent samples. Exoplanets provide proper (non-pseudo) experimental replication in our search for life.

Gerda Horneck

With the current technologies there is a good chance of finding exoplanets with atmospheres of which the spectral analyses give some hints to a possible habitability of that planet or even to biosignatures that might be produced by indigenous life. However, it will not be possible to discover ‘‘life.’’ The only way to discover life beyond our Solar System would be by SETI, that is, to receive signals emitted by a technically advanced life-form.

There is a much higher chance of discovering life beyond Earth on planets or moons of our own Solar System, that is, places where we can send spacecraft and even land for *in situ* investigations.

James F. Kasting

The easiest place to identify extraterrestrial life, surprisingly enough, is on planets around other stars—not in our Solar System. Our Solar System could indeed harbor life on other planets or moons. The most likely place is Mars. Mars' surface is frozen solid, however, down to a depth of a kilometer or more; hence, finding extant life there entails sending astronauts with deep-drilling equipment. That will happen, but not in my lifetime. (I'm over 60.) By contrast, finding evidence for life on planets around other stars just requires building a big Terrestrial Planet Finder (TPF) space telescope. We know pretty well how to do this already. There are three possible designs: an internal coronagraph (TPF-C), an external occulter (TPF-O), and an infrared interferometer (TPF-I). All three missions are big and expensive, probably over $5 billion, and that's why they're not happening today. We have to wait for NASA's even-more-expensive James Webb Space Telescope to fly first, and then we can begin talking again about TPF. Even if TPF costs $10 billion—James Webb is $8.7 billion—it is still much cheaper than sending humans to Mars, which would likely cost hundreds of billions of dollars. I don't count one-way trips, such as that envisioned by Mars One, as I am not a fan of suicide missions.

If we do eventually fly TPF and find evidence for life on extrasolar planets, it will be disappointing to some. That's because the most we will be able to find is spectroscopic signatures of biomarker gases, such as O_2, O_3, and CH_4. If we do observe these gases on another planet, debate is sure to ensue as to whether these gases are legitimate biomarkers or whether they might be generated abiotically. Indeed, that debate has already begun, and TPF has not yet even been started! But if we find such evidence, we can follow up on it by putting up a still bigger TPF telescope or, alternatively, by doing a similar mission at a different wavelength. (TPF-C and TPF-O would operate in the visible/near-infrared; TPF-I would operate in the thermal infrared.) So, physicists like me might eventually be convinced that life exists elsewhere. Biologists, however, are not likely to be satisfied. They would much rather get their hands on a real, live extraterrestrial organism so that they could examine it under a microscope—or maybe shake hands with it—and see what makes it work. We won't be able to do that by making remote observations. If that is the type of evidence you are looking for, your best bet is Mars. But I hope you are under 20 as you are reading this, because it may be many decades before we can get there with a well-equipped deep-drilling team.

Charles H. Lineweaver

The question seems to be asking: Which seems more likely, detection of life (A) in our Solar System or (B) outside our solar system? A and B seem equally likely to me. Detection of life in the martian subsurface would be the most likely A. Using the Lovelock criterion for the detection of chemical disequilibrium in exoplanetary atmospheres would be the most likely B. The timescale for either will be about 10–20 years. However, I suspect that ''our first discovery of life beyond the confines of Earth'' will be much more ambiguous and tentative than is generally assumed. Our understanding of life is still vague, and I don't think our tentative definitions of life are universal enough to apply to life beyond Earth. For example, if we define life à la Prigogine, as a far-from-equilibrium dissipative system, we have already discovered life beyond the confines of Earth. This discovery does not seem to satisfy many astrobiologists. The point is that the ''first discovery'' of a thing depends crucially on our understanding of the thing or on our definition of the thing. I think we should take this third possibility more seriously: (C) We will detect life by a paradigm shift in our understanding of life, based on investigations of the origin of life on Earth and based on deeper insights into what we now call the transition from nonlife to life. One example is viruses. Viruses may have diverged so early from the forms of life that led to us that we have difficulty recognizing them as our ancestors.

François Raulin

Exoplanet science is indeed very quickly evolving. We are now able to detect Earth-like exoplanets, and our capability of identifying some of the atmospheric constituents—at least of the largest exoplanets—is drastically increasing. It seems likely that within 10 years we will be able to determine the main composition of the most promising exoplanets for astrobiology. Now the question of unambiguous atmospheric biomarkers is still fully open. The presence of noticeable mole fraction of ozone (and/or oxygen), together with water vapor and carbon dioxide in a planetary atmosphere, is a good sign, but it could be a false positive for the potential presence of biophotosynthetic activity in the corresponding environment. The same applies with the simultaneous presence of chemically oxidizing and reducing compounds in the atmosphere. The presence of life may be the cause of such an out-of-equilibrium state for that environment, but nonbiological processes—such as geochemical ones—may also be the explanation. The methane case in the martian atmosphere is a good illustration of that problem. On the contrary, the absence of oxygen or ozone in the atmosphere does not mean the absence of life but the absence of biophotosynthesis, which does not exclude the presence of other forms of life. Even the absence of biomarkers or of a noticeable atmosphere may be a false negative, since life may be present in the internal structure of the exoplanetary body, as suspected in the case of Europa in the Solar System. In the search for extraterrestrial life beyond the Solar System, in spite of its very speculative aspects, SETI remains the surer approach. Coupling modern SETI tools with the exoplanetary science may be the most promising way for detecting extraterrestrial life outside the Solar System within the several coming decades.

J. William Schopf

My hunch: Possible but improbable. I think it likely that such studies, well before the end of the current century, will detect non-equilibrium concentrations of gases (*e.g.,* oxygen or methane) in exoplanetary atmospheres—but these findings will be regarded by the scientific community only as ''strong hints'' of the existence of life, not *the discovery of life*. The scientifically accepted discovery of the existence of life elsewhere will, I imagine, require hard data rather than model-dependent hints (however strong and seemingly sensible they may be), and I imagine it to be at least possible that extraterrestrial life will be found first within our solar system.

Norman Sleep

I expect martian evidence to become stronger over time. The hurdle for the f-word—''fossil''—has been set high. I do expect claims of life, however, from exoplanets within 10 years. This evidence is likely to be weaker.

Werner von Bloh

The likelihood of a first discovery of life outside Earth depends strongly on the funding for extrasolar detection missions. NASA and ESA are currently focusing more on planetary missions in the Solar System. In my opinion, it will be rather difficult to find present life on Mars or on other targets in the Solar System. In contrast to Mars, life on Earth is a global feature actively transforming the surface and changing the composition of the atmosphere. Targets for life in the Solar System are more located in niches hidden beneath the surface. For a second Earth, we have to leave the Solar System and have to look at planets around stars similar to our sun. The first candidates for habitable Earth-like planets are mostly located around low-mass M stars. These planets are orbiting tidally locked with environmental conditions quite distinct from Earth. Finding evidence of life on an extrasolar planet may need probably another 20 years since the first detection of a planet around a main-sequence star. On the other hand, so-called super Earths have been detected earlier than previously thought. Therefore, the detection of life on other planets might happen earlier than expected. But this depends strongly on the probability that a habitable planet exhibits life and that the biosphere changes the atmospheric conditions to allow a remote detection. This probability is still unknown. In conclusion, it is difficult to estimate a certain probability for finding life on extrasolar planets. But if this happens, it will be most probably a result of an exoplanet or exomoon investigation.

Frances Westall

It is clear that our ability to identify exoplanets has greatly increased over the last couple of decades, some of which are considered to be Earth-like or potentially Earth-like. Identification of life on an exoplanet or exomoon is, on the other hand, an extremely arduous challenge. It is widely believed that the only detectable biosignature would be the concurrent presence of oxygen, methane, and water in the atmosphere of an exoplanet or exomoon. The majority of oxygen in the atmosphere of Earth is of biogenic origin, being a by-product of oxygenic photosynthesis. Although there is still much debate about when microorganisms with a metabolism capable of producing oxygen appeared, the geological record clearly shows that its widespread appearance in Earth's atmosphere did not occur until after the reduced materials at the surface of the planet had been oxidized, about 2.4 billion years ago (Ga). This is more than 2 Ga after the formation of Earth.

Oxygenic photosynthesizers are relatively advanced organisms, and the ''invention'' of oxygenic photosynthesis is considered to be the most fundamental evolutionary phenomenon after the appearance of life itself. While photosynthetic life uses sunlight as its energy source, pre-photosynthetic life (chemotrophs) used (and still uses) either chemical or organic substrates as its energy source. For example, hydrogen liberated by aqueous alteration of the basic volcanic rocks (especially common on early Earth) fuels chemolithotrophs while the oxidation of organic carbon provided energy for chemoorganotrophs. Oxygenic photosynthesis is believed to have evolved via the symbiotic association of non-oxygenic photosynthesizers using two different ways of taking advantage of energy from sunlight. In turn, it is believed that photosynthesizers appeared after chemotrophs, themselves an evolutionary step more advanced than the first cells.

However, the non-photosynthetic chemotrophic life-forms, while seemingly widely distributed on early Earth, did not produce a high biomass and did not affect the environment of Earth to the extent of producing a ''biosignature'' detectable at distance. Thus, it may well be the case that a planet or moon can host chemotrophic life-forms, but they will remain invisible and undetectable. On the other hand, if we consider the hypothesis that life is the consequence of a chemical continuum, we can consider that any planet or satellite having the ingredients of life (liquid water, carbon, nutrients, and energy) is likely to see life emerging. Carbon is one of the most common elements in the universe, and carbon molecules are numerous. Thus, if, in the future, it is possible to detect liquid water on a rocky body, it may be legitimate to infer that that planet could host life. But the step from inference to certainty will most likely require time and great effort. In the meantime, it is more likely that we will be able to detect life (past or present) within the Solar System.

Where are our highest priority astrobiology mission targets in the Solar System?

André Brack

The highest priority astrobiology mission target in the Solar System is Europa. Jupiter's satellite is one of the most enigmatic of the Galilean satellites. With a mean density of about 3.0 g cm^{-3}, the jovian satellite should be dominated by rocks. Ground-based spectroscopy, combined with gravity data, suggests that the satellite has an icy crust at least 10 km thick and a rocky interior. The Voyager images showed very few impact craters on Europa's surface, indicating recent, and probably continuing, resurfacing by cryovolcanic and tectonic processes. Images of Europa's surface taken by the Galileo spacecraft show surface features, iceberg-like rafted blocks, cracks, ridges, and dark bands, which are consistent with the presence of liquid water beneath the icy crust. Data from Galileo's Near-Infrared Mapping Spectrometer show hydrated salts which could be evaporites. The most convincing argument for the presence of an ocean of liquid water comes from Galileo's magnetometer. The instrument detected an induced magnetic field within Jupiter's strong magnetic field. The strength and response of the induced field require a near-surface, global conducting layer, most likely a layer of salty water (Chyba and Phillips, 2007; Sotin and Prieur, 2007). The tidal heat generated by variations of the huge gravity of Jupiter provides probably most of the heat necessary to melt the ice.

If liquid water is present within Europa, it is quite possible that it includes organic matter derived from hydrothermal vents (Fischer Tropsch) if (and oh! what a big if…) Europa possesses magma, meaning an internal temperature of about 1200°C to melt silicates. Terrestrial-like prebiotic organic chemistry and primitive life may therefore have developed in Europa's ocean. If Europa maintained tidal and/or hydrothermal activity in its subsurface until now, it is possible that microbial activity is still present. Thus, the possibility of an extraterrestrial life present in a subsurface ocean of Europa must be seriously considered, despite the huge radiation field from Jupiter.

Jorge E. Bueno Prieto

Astrobiology has concentrated its interest on Mars, Europa, Titan, and Enceladus, as a consequence of the Earth-like factors in each one of them.

The great interest of humankind towards Mars comes from its great potential to bear life due to evidence of water on that planet. Satellite images of the surface of Mars have shown many characteristics that have been interpreted as having been produced by water. Some of the channels are slim and deep, while others are wide and shallow.

When observing the surface of Mars, characteristics similar to those produced by Earth rivers may be identified. Water altered martian surface mineralogy: soluble salts in the water were evaporated into evaporites (typically minerals such as anhydrite, cast, and carbonates), and primary minerals like hydrate silicates are altered to generate clays and hydroxides.

Additionally to the proof of fluids on the surface of Mars, there is a great amount of proof from satellite images that Mars has had a significant thermal history. This is due to the fact that the Red Planet has a nucleus and mantle structure similar to that of Earth, but it seems to have a rigid crust instead of the flexible plate structure of Earth, although recent results from the Global Surveyor magnetometer from NASA indicate evidence of tectonic activity. This is shown by the presence of huge volcanoes, now probably extinct. The presence of those volcanoes indicates an enormous amount of molten rock or magma that erupted during martian history.

Possibly the most powerful drive towards space exploration is the search for other living organisms with which we share our space in the Cosmos. Mars has been the main axis in this story; from science fiction to reality, the Red Planet has been the focus of attention for scientists. Mars, in the past, may have been a more hospitable place for the development of life; its atmosphere, weather, tectonics, and the presence of water are some of its most outstanding characteristics for the development of life at some point on that planet.

The data that we have, for the moment, do not provide exact or convincing signs, in either sense, of the existence of life on Mars. The Viking and Curiosity probes have not found any evidence of life on the martian surface, or organic molecules that consolidate such expected positive results for the presence of life. However, there is still a possibility of life harbored in more hospitable or isolated areas than the surface, such as the subsoil.

Aside from Earth, Mars is the most appropriate planet on which to find evidence of life in our solar system. The projection is then directed towards future exploration missions aiming to focus on areas of the Red Planet that still generate expectations to find either biological fossils or life-forms. For now, Mars is still the most attractive of our neighboring planets on which to find life-forms different from those that we know on our own.

From what we know of Earth, where there is water, there is a high possibility for life to sprout. This is why many scientist have speculated on the possibility of life in Europa. Superficial ice is made up of oxygen and hydrogen, and the constant flow of radiation from Jupiter reacts with this ice to form free oxygen and other oxides such as hydrogen peroxide. The reactivity of oxygen is key to generating the energy that led to pluricellular life on our planet.

A valuable point of interest in our solar system is Titan. The chemical reactions that take place in its surface ocean seem similar to those that may have generated photosynthesis on Earth: methane is dissociated in the high atmosphere and links to nitrogen, forming a complex mixture of hydrocarbons and nitriles.

Methane fulfills the role of water on Earth, it forms clouds in the atmosphere as it condenses over the aerosols, it forms a methane rain with particles filling the torrents with a flowing black material. But now, the canyons and lakes in the area where the Cassini Huygens probe landed are dry because methane, as well as water, settles into the ground and leaves at the surface portions of organic matter that cover it with a tar-like material.

The Huygens probe landed on Titan on January 14, 2005, and the information it has sent has increased significantly our knowledge of the satellite. It is possible that Titan harbors prebiotic molecules. The low temperatures explain why life has not evolved on Titan, even though it has the necessary ingredients. Its cold is the reason why this moon is kept as Earth was probably 4,000 million years ago.

Titan is an excellent lab in which to learn more about the chemical and prebiotic processes that occurred on Earth at an atmospheric and superficial level. Future explorations will deliver new results that will bring us closer to the objectives of astrobiology.

Finally, the most recent of our objectives concerns Enceladus, whose density and distribution of impact craters suggest that its surface has been recently renewed, at least in some of its areas. In fact, and in a similar way as happens in Ganymede, Enceladus has two surfaces of different ages: one is densely characterized, and the other is covered in striations, as a possible result of fissural eruptions of liquid water from its interior ocean.

Charles Cockell

The highest priority astrobiology targets in the Solar System should be places that have the largest number of requirements for habitability definitively detected and co-located. They should also be relatively easily sampled and, if they turn out to be devoid of life, tell us something important about astrochemistry. The plumes of Enceladus, which exhibit the presence of organics, various cations and anions, and potentially liquid water, are therefore of huge astrobiological interest. Furthermore, if the organics in the plumes do not provide evidence of life, they will tell us important things about organic processing in the Universe and the subsurface inventory of organics in icy moons. Putative europan plumes may offer a similar opportunity.

Gerda Horneck

Astrobiology deals with the processes that may lead to the origin and evolution of life here on Earth and beyond. Therefore one has to differentiate according to the objective of that mission:

- Targets for understanding the processes of chemical (prebiotic) evolution are Titan, asteroids, and comets.
- Targets for searching for life beyond Earth are Mars, Europa, Enceladus, and others to be determined.

Highest priority should be given to the exploration of Mars, because there are many indications that early Mars and early Earth had a similar history. Finding indications of indigenous life on Mars, past or present, and analyzing it will contribute to a universal definition of life. So far, this is not possible, because we have only one example of life, that is, us.

Charles H. Lineweaver

For the near future (5–15 years) my prioritization would be Earth, the Moon, and Mars. For the more distant future: Venus, Titan, and Europa. I put Earth first because we are still woefully ignorant about the origin and limits of terrestrial life and what its universal features might be. Metagenomic studies of the entire planet are needed. Less biased and more open-ended searches need to be made of the variety of life on Earth, especially of the things about which there is controversy over whether they are alive or not: viruses, the biosphere, prions, small RNAs, and so on. Discovering shadow life or new deeply rooted and short-branched organisms would give us clues not only about the origin of life on Earth but also about what life is. Also, many insights about the nature of life will come from studies of the hot deep biosphere. I put the Moon second because I suspect that we may learn more about the origin of life on Earth by studying pieces of the Earth that were blasted off the Earth's surface ~4 billion years ago and have been relatively well preserved there ever since. The best preserved ~4 billion-year-old terrestrial rocks are probably on the Moon. My next priority would be a fossil-hunting mission on the martian surface or a search for extant life in the martian subsurface—the top meter or so.

François Raulin

My answer is largely adapted from ''Planetary Astrobiology—The Outer Solar System'' (Raulin, 2009).

Astrobiology includes not only the search for extraterrestrial life but also the study of the origin and evolution of life on our planet, as well as the study of extraterrestrial organic and prebiotic chemistry. Consequently, there are different categories of planetary bodies of prime interest for astrobiology. There are bodies where a complex organic chemistry is going on. The study of the chemical processes and structures involved in this chemistry is crucial for understanding the general processes of complexification of matter in the Universe, which is essential in the evolutionary steps to life. In that domain the study of the organic chemistry in comets and meteorites is of paramount importance, since their organic content has probably directly participated in the prebiotic chemistry on Earth. There are also planetary bodies which show today some similarities with our planet before the emergence of life. The study of such environments is also of tremendous importance, since most of the conditions which were present on primitive Earth have disappeared today, erased by geological processes and by life itself. Now, if we want to understand the processes which allowed the origin of life on Earth and check our ideas and concepts, we need to place them in a realistic environment: the availability today of planetary bodies showing analogies with early Earth is a unique opportunity. In that domain, Titan, the largest satellite of Saturn, is a precious target.

And finally, there are extraterrestrial planetary bodies where life, either extinct or extant, may be present. Those places are characterized by past conditions compatible with the development of complex prebiotic processes over a period long enough for the emergence of life (or conditions compatible with the importation of living systems from other places), followed by conditions compatible with habitability. One of the main parameters which drives the habitability of a planetary body is the presence of liquid water. Mars, like Earth, very likely had large bodies of liquid water on its surface for long periods of time in its early history. This makes the Red Planet the most attractive body in the Solar System for searching for traces of extraterrestrial biosignatures. Indeed, if life was—or is still—present on Mars, those traces may be reachable today in the close subsurface, since the martian environment, in spite of a drastic evolution of its atmosphere, has probably kept part of these traces owing to the lack of strong tectonic activity.

But there are other places in the Solar System where liquid water is probably present. This is the case of three out of the four Galilean satellites of Jupiter: Ganymede, Callisto, and Europa. This is also the case of Titan, the largest satellite of Saturn and, more recently evidenced, that of Enceladus, a smaller satellite of the same giant planet. Although we have so far no direct evidence of these internal oceans, the most interesting cases are those of Europa and Enceladus, since if they exist, the internal liquid water bodies may be in contact with rocky materials, facilitating redox reactions that provide chemical energy to sustain prebiotic processes as well as energy for living systems.

Thus, all together, the highest priority astrobiology mission targets appear to be Mars, Europa, Titan, and Enceladus.

J. William Schopf

My guess: As best I can tell, we are on the right track. Given what we know now about Solar System bodies and, perhaps even more importantly, about the limits of living systems—their requirements, adaptability, and the nature of life's origin—the research strategy of recent decades and the missions planned for the near future seem the most likely to yield fruitful results.

Norman Sleep

Mars and Titan. Mars has had liquid water and chemical disequilibria. It was open for habitation well before Earth was. Titan has liquid water at depth. There also may be strange methane-based life.

Frances Westall

There are two types of astrobiological targets in the Solar System, the rocky planet Mars and a number of icy satellites orbiting Jupiter and Saturn. Mars was certainly habitable on its surface in the past and may still be at depth. Other planets and satellites may have been habitable in the past when their cores were hot and liquid water was in contact with a warm, rocky surface. Some of them may still be habitable if there is still liquid water in contact with warm rocks and a chemical or heat source of energy. Of these, Enceladus appears to have pockets of liquid water within its icy crust, as may Europa and Callisto. If life on Earth is taken as an example, once it has appeared, it is difficult to extinguish unless all its ingredients become simultaneously unavailable. If it becomes extinguished, the ''right'' conditions for its reappearance need to be present for some hundreds of thousands to millions of years. Thus, if environmental conditions degrade on a planet, for instance the desertification of Mars or the freezing of Enceladus, Europa, and Callisto, it will be very difficult for life to reappear.

Given these reflections and the likelihood of finding traces of life, Mars is the first choice for an astrobiology mission. It is the closest planet to Earth and, considering that it will be necessary to verify tentative *in situ* identifications of past (or even present) life by bringing relevant samples back to Earth for sophisticated analyses in a terrestrial laboratory, a sample return mission to Mars is more feasible than one to the outer satellites. Nevertheless, the challenge of finding past traces of life on Mars will require greater investment than made to date. The Pre-Noachian to Noachian period was probably more hospitable, especially large, lake-filled impact craters that could have been habitable over periods of time long enough for life to have appeared; therefore terrains of this age are most likely to contain signs of life. However, it is not impossible that younger terrains with lake-filled impact craters could have hosted life, if viable cells could have reached the potential habitats.

While it is generally believed that the ozone screen was not present during the Archean, there is accumulating evidence that during that time microbes inhabited shallow environments on Earth. How did they protect themselves from harmful UV?

André Brack

It is assumed that the first living microorganisms were heterotrophic species using extraterrestrial ingredients delivered by the heavy bombardment. They lived in UV-protected environments, either in deep water or in clay-containing turbid water.

A large fraction of organic matter on primitive Earth was of extraterrestrial origin, as documented by the presence of carbonaceous components in meteorites and micrometeorites. This is supported by estimates of micrometeorite flux from Antarctica, which suggest that about 2.5×10^{19} kg in the form of kerogen was delivered to primitive Earth over 200 million years (Maurette and Brack, 2006). The life cycle of interstellar amino acids, from their formation in the interstellar medium to their landing on Earth in meteorites, has been tested, both in the laboratory and in space (Brack, 2007b). One amino acid, α-amino isobutyric acid, has been identified in Antarctic micrometeorites (Matrajt *et al.,* 2004). These grains contain also a high proportion of metallic sulfides, oxides, and clay minerals, a rich variety of inorganic catalysts which could have promoted the reactions of the carbonaceous material which lead to the origin of life.

At the end of the heavy bombardment, the microorganisms had to exploit another source of organics. They began to extract their carbon from atmospheric carbon dioxide via non-oxygenic photosynthesis. Becoming autotrophic species, they needed the solar flux as an energy source but had to protect themselves from harmful UV. One way would have been to form clumps or aggregates to enhance their survivability under high dosage of UV (Yang *et al.,* 2008). Another way could have been the selection of halophilic microorganisms, since osmophilic *Haloarcula* and the halophilic *Synechococcus* survived the 2-week exposure to solar UV in Earth orbit aboard the Biopan facility (Mancinelli *et al.,* 1998).

The early use of non-oxygenic photosynthesis is supported by the presence of a fossilized, well-developed microbial mat that formed in an evaporitic littoral environment in a 3.5–3.3 Ga old formation from the Barberton greenstone belt. The mat was constructed by 0.25 μm filaments that produced copious quantities of extracellular polymeric substances, representing probably anoxygenic photosynthesizers. An embedded suite of evaporite minerals and desiccation cracks in the surface of the mat demonstrates that it was periodically exposed to the air in an evaporitic environment. The authors concluded that DNA-damaging UV radiation fluxes at the surface of Earth at this period must have been low (absorbed by CO_2, H_2O, a thin organic haze from photodissociated CH_4, or SO_2 from volcanic outgassing; scattered by volcanic, and periodically, meteoritic dust, as well as by the upper layers of the microbial mat) and/or that the microorganisms exhibited efficient gene repair/survival strategies (Westall *et al.,* 2006, 2011).

Charles Cockell

Ultraviolet radiation is damaging, but its biological role is often overstated. On land masses, just a few millimetres of rock will preferentially attenuate biologically effective UV irradiances one to three orders of magnitude more compared to photosynthetically active radiation, providing a clement zone for phototrophs. In the oceans and water bodies, short wavelengths such as UVC (200–280 nm) are preferentially absorbed by water compared to longer wavelengths. Impurities and particles can help scatter this radiation. Even if one assumes the worst case (that microbes had no biological screening), then water bodies and land masses could have been colonized. However, we know that microbes use ‘‘matting’’ and have specific evolutionary innovations, such as UV screening compounds and repair processes, that would further have mitigated the deleterious effects of UV radiation. In the absence of an ozone shield, exposed surfaces and shallow waters would have been more damaging to life than today, but finding evidence of organisms inhabiting such environments would not be surprising.

Gerda Horneck

Model calculations and experiments in outer space have demonstrated that without the stratospheric ozone layer, the biological efficiency of the terrestrial UV-radiation climate would be increased by three orders of magnitude, compared to present-day conditions. This would easily kill all microorganisms exposed to it. There are three ways of mitigating the harmful biological effects of early Earth UV radiation: (i) escaping, that is, searching the shadow; (ii) screening, that is, developing UV-protective pigments; and (iii) repair, that is, developing efficient repair systems for DNA damage. On the other hand, UV radiation is a strong mutagen that might have efficiently driven biological evolution on early Earth.

Charles H. Lineweaver

I think this is a nonissue. To see how effectively 5 cm of water blocks solar UV, look at Fig. 7 of Lineweaver and Chopra (2012). Even on land, life could have thrived in the shade under a rock or inside a rock. And finally, there would be the evolution of DNA repair mechanisms to rapidly repair the double strand breaks produced by UV.

François Raulin

Protection of early life from harmful UV does not seem to be really a big challenge. If early life was first developing in the primitive terrestrial oceans and was mainly located at the bottom of these oceans, close to the deep-sea primordial hydrothermal vents, water, mixed with many organic and mineral particles likely to have been present in that environment, may have been the needed protecting screen. The protection may also have been achieved by the atmosphere itself, in particular with the likely presence of atmospheric haze particles (as this is currently the case with Titan). Such haze could have efficiently blocked the harmful UV light, making possible the development of living systems at the surface of primitive Earth.

J. William Schopf

I have thought about this for a number of years, and I have come to regard it as not a particularly vexing problem. Its answer, I think, comes from understanding the history of Earth’s atmosphere (items 1–3, below) and microbial evolutionary biology (4–10). My explanation is as follows:

(1) The early Sun produced appreciably more UV than it does at present.
(2) Prior to the buildup of atmospheric oxygen at the ~2450–2200 Ma Great Oxidation Event (GOE), ambient-level oxygen remained low (even after the origin of O_2-producing cyanobacteria, the oxygen having been sponged up by reaction with previously unoxidized volcanic gases and mineral substrates).
(3) With this development, the GOE, an UV-absorbing ozone (O_3) layer became established.
(4) Fossil stromatolites establish that photoautotrophs, the earliest evolved being non-oxygen-producing photosynthetic bacteria, were present 3500 Ma ago, much earlier than the GOE.
(5) Cyanobacteria, mutant derivatives of non-oxygen-producing photosynthetic bacteria, also originated well before the GOE.
(6) The most primitive photoautotrophs were unicellular coccoidal phytoplankton. Such living prokaryotes have gas vacuoles—which microbiologists explain as enabling these microbes to position themselves in the

water column for optimum nutrient absorption (which they evidently do) but which I imagine to be an evolutionary derivative that originally permitted primitive successful lineages to position themselves in the photic zone beneath wave-base and, thus, avoid being ‘‘fried’’ by the UV flux at and near the water-atmosphere interface.

(7) Near shore, shallow water photic zone settings, potentially exploitable by photoautotrophs, were initially uninhabited.

(8) To occupy this UV-infused but otherwise potentially favorable habitat, successful phototrophic microbes secreted large amounts of extracellular mucilage (mostly 5-carbon sugars) that enabled them to attach to benthic substrates and, thus, be protected by overlying water from the deleterious UV. (In terms of bioenergetics, this or some other explanation must apply: such microbes expend a large amount of cellular energy to produce such mucilage, energy-rich sugars they would otherwise metabolize. Many microbiologists regard these as ‘‘waste products,’’ but their genetically determined production makes little sense unless it was initially of adaptive value.)

(9) Such microbes developed an impressively effective set of genetically based UV-damage repair mechanisms (*e.g.,* if one wishes to ‘‘clean’’ a population of cyanobacteria from adhering bacteria to produce an axenic monospecific culture, the simplest and most commonly used technique is to flood the microbes with UV—which is lethal to associated aerobic bacteria but has no effect on the cyanobacteria because of their genetic heritage).

(10) From these developments, photoautotroph-formed stromatolites had become prevalent in shallow water settings by 3500 Ma ago. Their presence evidences the adaptation of living systems to a seemingly hostile environment and indicates that the origin of life must have occurred appreciably earlier.

Given the foregoing, the UV flux of the early environment—however fierce one may imagine it to have been—is a problem that was surmounted by biological evolution. Evolving living systems are opportunistic. Over all of Earth history, life has evolved to occupy open space where it ultimately can thrive—in this instance, from a planktonic open marine to a benthic near-shore shallow water setting; later, from an aqueous environment to near-shore marshes (with the origin of spore-producing land plants followed by amphibians); and then, later still, by occupation of highlands (by the advent of pollen-producing seed plants and the subsequent evolution of egg-laying reptiles). Given biological time (markedly short in comparison with geological time), life has evolved, life has coped. The deleterious intracellular problems posed by UV and cyanobacterially produced O_2 (and its mutation-producing derivative, singlet oxygen) were solved early, in the Archean, by innovative microbial biological evolution.

Norman Sleep

I have never seen UV as much of a problem. Life survives in the modern ozone hole. A shield needs only to stop UV and let some visible light through. A little bit of water or soil works. A layer of their dead microbes shields the live ones below.

Frances Westall

The evidence for life within the photic zone on early Earth is indeed strong. Westall *et al.* (2006, 2011) described a photosynthetic microbial mat exhibiting desiccation cracks and encrusted with evaporite minerals that was exposed on a beach to the air. Many other occurrences of photosynthetic mats have also been documented (*e.g.,* Walsh, 1992; Hofmann *et al.,* 1999; Tice and Lowe, 2004; Allwood *et al.,* 2006). Cockell and Raven (2004) calculated that the flux of DNA-damaging UV radiation to the surface of early Earth was of the order of 50 W/m^2 and up to 1000 W/m^2 in a worst-case scenario. However, the relative abundance of the traces of photosynthetic mats implies that these organisms managed to survive very well. Various mechanisms can be invoked, such as the presence of UV-protecting pigments, an effective gene-repair mechanism, and relatively rapid reproduction.

Which current hypothesis for the origin of life on Earth is most promising?

André Brack

After the historical experiment of Stanley Miller in 1953, chemists tried to synthesize a cell-like system including precursors of RNA, protein enzymes and membranes. Since RNA was shown to be able to act simultaneously as an information and catalytic molecule, RNA was considered to be the first living system on primitive Earth. However, since the direct formation of RNA under prebiotic conditions has not yet been convincingly demonstrated, RNA is not a commonly accepted model for the origin of life. It has been suggested that peptide nucleic acid (PNA) might have been the first genetic material that preceded the RNA world. PNA forms very stable double helical structures and even stable triple helices. However, the fact that activated PNA monomers have a strong tendency to cyclize, which makes the formation of oligomers very difficult under prebiotic conditions, and PNA hydrolyzes rather rapidly restricts the chances of PNA to have ever accumulated in the primitive oceans.

Some chemists are now tempted to consider that primitive self-replicating systems must have used simpler informational molecules than biological nucleic acids or their analogues. Since self-replication is, by definition, autocatalysis, they are searching for simple autocatalytic molecules capable of mutation and selection developing on mineral surfaces, that is, chemistry ‘‘on the rocks.’’ As heirs of Marcelin Berthelot, who wrote ‘‘Chemistry creates its own object,’’ organic chemists are generally proud to control each step of the process, from the conception to the final product. So far, they have failed to reconstruct primitive life in a test tube. Another strategy would be to mimic as closely as possible the primeval broth and let the system evolve for days and months. Doing so, chemists will no longer control the conceptual step, but this is perhaps the price to pay to realize a dream which is now more than 60 years old.

Jorge E. Bueno Prieto

The origin of life continues to be one of the unanswered questions in natural science. Since man began to question the phenomena around him, his own origin and his surrounding living beings, a series of proposals and ideas were generated. Up until now, life as we know it is the outcome of a process that took millions and millions of years, where geological, chemical, and physical factors, to name a few, intervened to top off with a biological process; that's how it plays a main role in the interdisciplinary effort to pursue this question as a scientific problem. During an initial challenge, chemical factors appeared as main characters, which through their specific associations generated organic molecules, which later on interacted and developed unique structural and behavioral characteristics. For this reason, their relationship to their external surroundings was evident, reaching a level of complexity with exclusive characteristics to experiment the transition from nonlife to life.

Panspermia includes a series of theories that have as common ground the consideration that the origin of living beings is based on basal organisms or activating particles of life that are distributed throughout space. The Greek philosopher, Anaxagoras, was the first to establish the term *panspermia* to explain the appearance of organisms in mud. It wasn't until the XIX and XX centuries that the chemist Svante Arrhenius stated that such ''spores'' could have travelled through space until they reached Earth. Today, we know that it is possible for extremophilic bacteria to withstand non-earthly environments, as is the case of *Streptococcus mitis* in the lunar environment. However, further studies are required to learn more about the adaptation and development processes of microorganisms in environments beyond Earth and to be able to support in a concrete way this part of the theory of panspermia.

This is where the interest in submarine hydrothermal sources as chemical nurseries for life comes from. In fact, computer simulations indicate that organic matter may have an origin in extreme environments. Gunter Wächtershäuser's proposal on a thermophilic origin of autotrophic life strengthened the attention towards submarine chimneys.

This author suggests that the synthesis of anoxic pyrite was the source of energy and electrons for carbon dioxide, which favored the fixation and genesis of all other organic components in the newborn living matter. In other words, Wächtershäuser presented a substitute for the prebiotic soup through a primitive autotroph bi-dimensional metabolism on the surface of pyrite, which is favored by high temperatures and uses reduced sulfur gases which are abundant in submarine hydrothermal sources.

At this point, the theories established up until now about the origin of life cannot be satisfactory on their own, but if we generate an integrated vision, we can create a sustained network to explain the appearance of life on planet Earth. We must highlight, among what we have studied from living organisms, that the flow of matter and energy through molecular systems allowed for the generation of more organized states, which were a nursery for the first genetic records. Thus, the origin of life was a process with ecological integration characteristics where the autonomous compartments developed in cells with hereditary features and evolutionary and adaptive capacity.

Charles Cockell

An attractive idea that has been proposed and is worth investigation is that the entire Hadean Earth was a giant prebiological reactor, with organic syntheses occurring in many of the environments which tend to be a focus of particular theories. Impact hydrothermal systems, deep ocean volcanic vents, rocks on beaches all offer locations for organic concentration and complexification in addition to complex organics that were exogenously delivered. It seems possible that many environments were potential locations for the assembly of components of life (such as membranes) that were being flushed into the wider environmental system. The final assembly site where these components came together into an entity that replicated might have been any location where concentration was possible, but perhaps not necessarily the same location where the precursors were synthesized.

David Deamer

The unit of life today is a highly complex system of macromolecules in cellular compartments, and the earliest forms of life were presumably primitive cellular systems composed of simpler versions of catalytic and genetic polymers. If this is correct, then it seems inescapable that nothing came ''first.'' Instead, the origin of life involved a natural version of combinatorial chemistry in which amphiphilic molecules spontaneously assembled into compartments that encapsulated random polymers. These were synthesized by chemical reactions such as condensation to form ester linkages. Vast numbers of such microscopic compartments were continuously being produced, each different from all the rest, and each a kind of natural experiment. By chance, a few rare compartments happened to contain polymers that could catalyze growth by polymerization, using their own monomer sequences as templates. Those compartments would quickly take over, while inactive compartments would be left behind. I suppose my bottom line is that it is not very helpful to think of metabolism first or genes first. If I had to come up with a more useful phrase, I suppose it would be *systems first.*

Niles Lehman

In my opinion, there will soon be a synthesis between the ''RNA world'' concept and that of metabolism-first ideas. There are promising suggestions that these two—sometimes competing—viewpoints can find common and complementary ground. Experiments into autocatalytic cycles involving networks of cooperating organic molecules should be able to incorporate information-type chemistry. By information-type chemistry I mean the existence of relatively weak and readily reversible bonds, such as hydrogen bonds, in which spatial patterns can specify a certain degree of pattern recognition and hence primitive coding. When this can be merged with a set of organic or organometallic and/or photoorganic reactions that are self-sustaining, then we will have our best view into what could have initiated life on Earth.

Charles H. Lineweaver

I lean towards the hydrothermal vent models (*e.g.,* Martin, 2012). However, I would like to see efforts to combine metabolism-first models with replication-first models. ATP and other nucleoside triphosphates are good examples of ubiquitous biomolecules that are deeply involved at the most fundamental level with both replication *and* metabolism.

François Raulin

The concept of chemical evolution is largely accepted by the scientific community and gives a general frame for our understanding of the origin of life on Earth. Now there are several questions remaining in many of the different steps involved in this theory. Even the initial steps, involving relatively simple organic compounds, have different possible scenarios. The starting organic matter necessary for the subsequent prebiotic chemistry may have been produced in the atmosphere or in the vicinity of the hydrothermal deep sea vents, or may be of extraterrestrial origin, imported by meteorites, micrometeorites, or comets. However, there is no contradiction between these different possibilities, which, in fact, may have occurred together. The main and most important questions concern the following steps, and particularly the emergence of the first replicating system. In that field, the concept of dynamic kinetic stability may open new ways and initiate new approaches to study the question of the origin of the first replicating system. The idea is that

> all persistent replicating systems tend to evolve over time towards systems of greater dynamic kinetic stability, quite distinct from the traditional thermodynamic stability which conventionally dominates physical and chemical thinking. Significantly, that stability kind is generally found to be enhanced by increasing complexification, since added features in the replicating system that improve replication efficiency will be reproduced, thereby offering an explanation for the emergence of life's extraordinary complexity. (Pross and Pascal, 2013)

J. William Schopf

My preference: Though in some quarters there has been a groundswell of support for life originating in settings associated with deep marine fumaroles, I continue to prefer prebiotic atmospheric syntheses as proposed by Oparin and Haldane and shown plausible by Miller-Urey syntheses. Perhaps I am ''old school,'' but a Fischer–Tropsch–type (FTT) synthesis, because of its inherent complexity and numerous other limitations, seems to me an implausible source for generation of the types of organics in appropriate yields that I envision as being required for life to originate. Nevertheless, it is important to recognize that nonbiologically produced organics have as yet never been identified in the geological record—we have no direct evidence of the Oparin-Haldane ''primordial soup,'' regardless of its mode of synthesis. Thus, how and when life began continues to be a overwhelmingly important ''known unknown,'' a major problem that we know exists but for which we have no evidence, no firm solution (the lack of which I attribute to the virtual absence of a pre–3500 Ma old rock record where such evidence should be sequestered).

Norman Sleep

I pick one that has gotten little attention. Fluids circulate highly reduced peralkaline intrusions and lavas in Hadean arcs. The Na silicate and high pH stabilizes ribose. This molecular biology is Lambert's idea. The situation is inevitable, as subduction of the early massive CO_2 atmosphere was necessary to get habitable climate. Subducted oceanic crust was CO_2-rich. Low-pH rain and seawater were out of equilibrium with the vent fluid. Land origin might help. AGCT and U are UV resistant. Freeze thaw and dry wet concentrate and dilute solutes in the water. Erosion of the arc rocks might even make the whole ocean alkaline.

Frances Westall

The current hypotheses for the origin of life invoke the assemblage of the essential macromolecular constituents in different scenarii. It seems that some kind of enclosed system is necessary for housing the molecules important for metabolism and for reproduction, either within a lipid micelle or within the protective pore space of a porous rock (*e.g.,* a beehive-style hydrothermal vent structure) (Russell *et al.,* 2010). Previously, the debate centered on whether proteins came first or RNA, both being necessary for the creation of the other; now it appears that proteins could have functioned both for metabolism and reproduction (PNA).

The location for the appearance of life is also subject to debate. Three possible locations have been invoked, including hydrothermal vents (Russell *et al.,* 2010), the swash zone on a beach (Bada, 2004), or rivers on land (Benner *et al.,* 2010). The latter is unlikely because there were few exposed surfaces on early Earth, most of the ''primitive'' continents being submerged plateau-like structures. They were also considerably unstable on the relatively soft and tectonically, volcanically, and seismically active planet. Thus, river systems would not have existed for the lengths of time necessary for cells to appear. The first two locations, hydrothermal vent edifices and the beach swash zone, were common and may even have occurred relatively frequently together. Thus, assemblage of macromolecules on reactive mineral surfaces and concentration and elution of macromolecules in rock or sand grain–sized pore space on the beach could have been simultaneously favored.

What is the greatest challenge that needs to be resolved to synthesize life in the laboratory?

André Brack

The greatest challenge is to find autocatalytic organized molecular systems growing on mineral surfaces and making small errors. Adsorption onto mineral surfaces would decrease the degrees of freedom from 6 to 2, thus limiting the negative entropy variation close to zero. According to Wächtershäuser (2007), the carbonaceous starting material for the first living systems was carbon dioxide. Associated with H_2S and N_2 in contact with the sulphur-containing surfaces of Fe, Ni, and Co, carbon dioxide would have been reduced via the hydrogen provided by the oxidative formation of pyrite (FeS_2) from troilite (FeS) and hydrogen sulphide. Pyrite has positive surface charges and bonds the products of carbon dioxide reduction, giving rise to a two-dimensional reaction system, a ''surface metabolism'' that, later on, included autocatalytic cycles. However, it is difficult to imagine how such an autotrophic ''metabolic first'' scenario would have easily generated evolving autocatalytic molecular systems. Preformed amino acids were probably present in the primitive oceans. If we imagine some primers adsorbed on mineral surfaces surrounded by monomers, autocatalytic growth of the primers followed by chain cleavages would represent a way to heterotrophic self-reproduction of specific sequences. We showed that peptides with alternating hydrophilic and hydrophobic amino acids, such as alternating poly (Glu-Leu), adopt a β-sheet structure in the presence of crystalline CdS (Bertrand and Brack, 2000). The β-sheet structure is stereoselective and thermostable (Brack, 2011). Practically, short homochiral oligo (Glu-Leu) primers would be adsorbed on CdS and fed with racemic activated glutamic acid and leucine. If some mineral-assisted autocatalytic chain elongation occurs, alternating homochiral sequences should be preferentially synthesized. This is not yet life, but such a process would fill the space with selected homochiral catalytic layers.

Jorge E. Bueno Prieto

This is one of the biggest challenges for current biology and without any effective results yet, due to independent and specific lab work. It is necessary to establish a protocol linked to computer simulation and further practical implementation of processes and mechanisms, such as the synthesis of lipid and protein chains. As well as the first protobiological structures on Earth required an isolating structure (now called a cell membrane or cellular wall), they also needed an energetic means and a replication factor to guarantee their continuity.

And these are the steps to execute in the lab, to reach at least a basal stage of synthesis of life. The tests done up until now may evidence the formation of proteinoid structures such as those proposed by Sidney Fox. The experiments have also shown that the simple mixture of simple fatty acids and glycerol is formed by mixtures between mono-, di-, and triglycerides under mild conditions, thus forming basic compartments. Likewise, the mechanisms to establish and develop self-catalytic molecules have been feasible in computer simulations and practical lab events.

I consider that a joint experimental design is necessary, where each one of the previously, separately, undertaken stages is oriented in a phased and integrated way, so that it will make ''independence'' and ''integration'' easy components to determine the adaptation and chemical selection that the molecules followed on Earth for the sprouting of life.

Charles Cockell

We know very little about the minimal gene set required for organisms to grow in natural extreme environments. A great challenge is to determine exactly what these minimal gene sets are. For example, what is the minimal set of genes required for an organism to grow in basalt and to assimilate the basic cations, anions, and energy sources (for example, iron-based chemolithotrophy) available in an igneous environment? Answering questions like this one would enable us to synthesize particular kinds of analog ancient life. These ''synthetic deep branchers'' would be useful for understanding the simplest possible forms of life on early Earth and determining the minimum architecture for a self-replicating organism to persist on and in the surface of a rocky planet.

David Deamer

Given my answer to the fourth question, the first challenge will be to discover a system of encapsulated polymers that can use nutrients and an energy source to undergo growth by catalyzed polymerization, followed by replication using their own monomer sequences as genetic information. The first form of artificial life will not need metabolism, because substrates and chemical energy will be provided by the investigator. The second challenge will be to find a way for the membranous compartment to grow along with the polymers and then divide into daughter cells. The third challenge will be for the various growth and replication processes to be regulated by feedback mechanisms; otherwise the system will self-destruct.

Niles Lehman

The greatest challenge will be to explore the range of organic chemistry that was not only prebiotically feasible but also exhibits the properties I outlined in my response to Question 4. The hurdle will be to take a systems chemistry approach to abiotic organic chemistry, with the probable inclusion of some inorganic (metal ion) catalyst. This is difficult because we as scientists all have our own backgrounds and specialties, yet this problem needs a collaborative and synergistic approach from a variety of chemical and biological subdisciplines. To make matters worse, we will never know whether we've succeeded, because we will not have a time machine to check our answers. Nevertheless, I am optimistic that within 20–30 years we will have a model system that is a realistic approximation of what took place on our earth some 4 billion years ago.

Charles H. Lineweaver

The greatest challenge is the tar problem that Bob Shapiro championed. Tar forms readily from organics and seems to be a biochemical attractor. Prebiotic syntheses contain detailed descriptions of the chemistry presented but seldom consider the likelihood of this chemistry in the context of early Earth (Shapiro, 2006).

Juan Pérez-Mercader

Impressive progress in the application of molecular genetics and biotechnology to the field of ''synthetic biology'' has recently drawn a lot of attention. Many refer to these activities as ''synthetic life'' and their results as pertaining to the ''synthesis of life,'' whereby they mean the successful generation of chromosomes or full living systems that are the result of more or less extensive genetic modifications of some extant living forms. Of great interest in this context is also the construction of complex chemical systems that emulate natural living systems by using complex chemical species seen in extant life or modified natural chemical species, together with the assemblage of the various basic components of the ''synthetic living system,'' including the vesicle, replicating polymers, and so on. This, of course, is very exciting, is being done to differing degrees, and is vigorously investigated in protocells, phages, bacteria, and yeast. Many challenges remain, including what would be understood as a ''minimal'' organism and how to accommodate Darwinian evolution.

However, if instead of the above what is meant by ''synthesis of life in the laboratory'' is the *ex novo* creation of a chemical system capable of behaving like an extant living system, the situation and some of the challenges are quite different from the ones in the previous paragraph. The *ex novo* creation would probably entail the use of parts or structural assembly strategies not necessarily found in extant natural life. The problem is now more akin to actually identifying and putting together from scratch a combination of chemistries and materials capable of supporting several properties. To qualify as a ''synthetic living system,'' such a system would need to be based in chemistry and display a set of concomitant properties. The system must (1) carry out the handling of information, (2) be able to metabolize resources found in its environment to construct many of its parts and guarantee its coherent functioning (''living''), (3) carry out programmed system self-replication using the ad hoc parts synthesized by the system itself, and (4) be able to display some form of evolution, eventually including Darwinian evolution. All the above properties would probably inform and affect each other to guarantee the integrity of this peculiar ''living system.'' There are many challenges in this scenario, but in my opinion the most basic are in determining the conditions and actual chemistry (or chemistries) capable of supporting some form of ''programmed self-replication'' while also accommodating adaptive evolution in the context of the simultaneous expression of the above four properties.

Even if successful, and for the two classes of schemes we have mentioned, once the systems have been synthesized, additional challenges will appear when trying to establish a potential connection to the origin of life on Earth. For example, questions related to the natural chemical pathways that might have generated the molecular species involved in the synthesis of the system, or related to the potential connection of the processes underlying the synthesis and assembly with some form of natural planetary environments, among many other questions, will still have to be answered.

François Raulin

Although there are promising hypotheses to approach the question of the origin of life on Earth, and in particular the problem of the transition from nonliving to living systems, such as the concept of dynamic kinetic stability mentioned above, there are many challenging aspects. The greatest challenge is probably the time parameter. Indeed, it seems likely that life emerged on Earth after a long chemical evolution. What does ''long'' mean? Difficult to answer: it could be as short as 10^3 to 10^4 years, which may seem very short for many scientists. However, if this is almost instantaneous at the geological timescale, at the poor human scientist timescale it's awfully long, and no experiment could be carried out to mimic prebiotic processes in the laboratory over such a long duration of time. Thus the only way remaining to check our hypotheses on the complete scenario from the evolution of simple nonliving systems to the emergence of the first replicating entities is numerical simulation. But this requires so many parameters that the task seems almost impossible…

J. William Schopf

My notion: From my (perhaps myopic and overly simplistic) perspective, the outlines of life's origin are not difficult to understand.

(1) The elements of life, CHON, are universally plentiful, four of the five most abundant elements in the Universe (with the fifth, He, being inert).
(2) CHON + energy (*e.g.,* UV from stars, atmospheric lightning discharge) = monomers (*cf.* Miller-Urey syntheses).
(3) Monomers + aqueous environment (to protect prebiotic organics from destruction by UV) + concentration/assembly/ordering (*e.g.,* on drying clays; Ferris publications) = polymers.
(4) Some such polymers presumably incorporated both gene-like information and enzyme-like catalytic activity (*cf.* ribozymes; Cech publications).
(5) Earliest life would thus have been heterotrophic (arising from and metabolically processing prebiotic organics of the Oparin-Haldane ''primordial consommé''); the primitive ''RNA World'' would actually have existed (with DNA being a later evolutionary derivative, as evidenced by the predominance of RNA in protein-synthesizing ribosomes); and early life may have been thermophilic (Stetter and Yamagishi publications).

Were this scenario to be correct, it would leave only one three-part *greatest challenge* for the laboratory synthesis of life, namely, demonstration of (1) the absorption of prebiotic ribozyme-like molecules into presumably ''soap bubble-like'' semipermeable compartments (precursors of cells); (2) the capability of such entities to incorporate and derive energy from the breakdown of exogenous organics (a precursor to glycolytic fermentation); and (3) the capacity of such protocells to divide (a precursor to cell division, perhaps earliest a result of instabilities resulting from their increasing volume). By thereby completing a sequence leading plausibly to cell-based Darwinian evolution, Nobel Prizes will be handed out (though it will not be possible to know whether this or some other scenario in fact actually occurred).

Norman Sleep

One can make life now in ideal conditions. Pure reagents in test tubes did not show up when needed on early Earth. Experiments need to get more realistic conditions. There is a trade-off between realism and control. In addition, a process that worked over modest geological time on the whole planet may not happen (by chance) to work over limited lab time.

Frances Westall

The topic of the synthesis of life in the laboratory is rather outside my competence, but I understand that trying to construct the individual components in isolation, although useful in bringing a certain amount of understanding to the origins of these molecules, has not been sufficient to create life *ex novo*. Perhaps the answer lies in placing all the ingredients into a ''melting pot'' under early Earth conditions and letting the magic of chemical evolution take place. The main problem may be the geological timescales necessary.

If you were awarded $1 billion for an astrobiology mission that would fly within the next 5 years, what would be your mission design, and where would your mission go?

André Brack

I would dedicate a mission to search for life in the ocean of Europa. Searching for life means, fundamentally, searching for sites offering both liquid water and carbon chemistry. This is not just an anthropocentric point of view; the basic ingredients of terrestrial life exhibit very specific properties demonstrated in the laboratory (Brack, 2010). This couple appears therefore as the most appropriate to start life, that is, a chemical system autocatalytic in essence which has the capacity to evolve. Titan hosts a very active organic chemistry, but the very low surface temperature does not allow the presence of liquid water. Some buried aquifers are predicted by models but remain still to be discovered.

The most likely sites for europan life would be at hydrothermal vents below the most recently resurfaced area. Biological processes in and around hydrothermal vents could produce biomarkers that would be erupted as traces in cryovolcanic eruptions and thereby be available at the surface for *in situ* analysis.

The mission would have to map the surface to identify interesting evaporites, to detect indications of a magma, and to analyze the selected evaporites. Thus, an orbiter will map the surface in order to select interesting evaporites and analyze internal geodynamics, and a small lander will analyze the selected evaporites. However, whether $1 billion would be enough to shield the instruments from radiation is questionable. Positive data would trigger a new mission capable of making a borehole through the ice in order to deploy a robotic submersible.

Jorge E. Bueno Prieto

My astrobiological mission would be based on the perforation of Europa's crust through a robotic probe that could cut through the solid limit and adapt as a submarine to explore the water environment of this moon and generate a series of chemical, biological, and geothermal tests.

(1) Robotic probe
(2) Perforation of the cortex
(3) Chemical analysis of water
(4) Geological mapping
(5) Tracking biosignatures

In other words, prove the possibility of the presence of life in the ocean of this moon, based on its three properties which are up until now fundamental and derived from life on Earth: an ocean of liquid water, a source of energy, and an amount of organic elements whose origin can be identified through meteorites and comets that have deposited these chemicals throughout geological eras, as in the rest of our Solar System. Such possibility of life may happen at a microscopic level, based on bacteria that survive through the synthesis of chemical elements on the bottom of the ocean, but there may also be an evolution, or generation of biota from bacteria to multicellular organisms which are more complex and adapted to an environment limited by its access to light.

It would be invaluable to know through this exploration the maintenance of thermal sources at its bottom and establish the nutritional sources for bacteria that retrieve their food through chemical synthesis. For this reason there is the possibility of taking a chemical laboratory to verify if there are any isotopic anomalies on the frozen surface of Europa that reveal the presence of a colony of bacteria, as well as a geo-sensor that would determine the drastic geological changes derived from the influence of Jupiter and that have favored the energetic interaction of this moon with the springing of life.

Charles Cockell

One billion dollars puts serious constraints on what one can do, but it would be excellent if someone could spend this money on designing tiny, mass-produced, standardized, modularized, and cheap spacecraft with organic detection apparatus (*e.g.*, miniaturized mass spectrometers) that could be sent into multiple planetary locations where complex organics exist. They would have the major objective of characterizing organics and their distribution. These Organic Mapping Craft (OMCs) would be slung through the plumes of Enceladus, through the atmosphere of Titan, landed on Europa, Ganymede, Callisto, lunar polar craters, comets, and other bodies with organic-containing surfaces, plumes, and atmospheres. They would generate a huge standardized comparable inventory and map of organics in our solar system, including possible prebiotic compounds, maybe even life. These maps would allow us to understand the processing and distribution of organics and the components of life in star systems in general.

David Deamer

I would design an advanced version of Curiosity and send it to Mars, taking into account all that we have learned so far. The rover and instrument package should have the ability to drill down into what appear to be ancient lake beds with underlying ice (Heldmann *et al.,* 2014) and bring samples up for analysis. Besides the usual instrument package, I would include a solid state nanopore device as a biosensor. Nanopores have single-molecule resolution and are capable of detecting molecules as small as nucleotides. If life ever existed on Mars, it seems likely that remnants of polymers would be preserved in subsurface ice, and we now know enough about nanopore analysis to be able to interpret any signals that might be detected.

Gerda Horneck

ExoMars, but with more sophisticated instrumentation, as it was designed at the beginning with the aims to

- Search for signatures of extinct life
- Search for signatures of extant life

Assessing the habitability of Mars in preparation of future human missions to Mars.

Charles H. Lineweaver

I'm torn between two missions. One mission would be a version of what used to be called TPF/Darwin. The goal would be to do infrared spectroscopy from the Sun-Earth

L2, on the atmospheres of terrestrial planets to find biosignature gases. The other mission would be a mission to planet Earth to look for new life-forms on Earth. These could be found through metagenomic surveys of the entire Earth (extending and broadening the scope of what Craig Venter has been doing, *e.g.,* Wu *et al.,* 2011) to include viruses, small RNAs, and possibly shorter-branched extremophiles that have different biochemistries than the ones we have looked for so far.

François Raulin

Well, well, we have to admit that $1 billion or even €1 billion is far from sufficient for flying the best astrobiology mission. Moreover, this would not be a one-scientist project but a project for a wide international community of scientists and engineers. Thus if this team—let's say *our team*—was awarded such an amount, we will use it—with the help of the whole community involved in the project—as a catalyst to collect at least twice that amount in particular in soliciting many national and international bodies involved in space exploration. What would be the target mission? Mars, Europa, or the Saturn system, with Titan and Enceladus? Within 5 years from now, Mars would look like the most easily reachable target, and the mission would be a robotic mission. With such a target, the challenge is to be able to explore the surface and the subsurface of the planet after selecting areas which would be the most promising for astrobiology. One of the best options would be to have the capacity to bring back to Earth samples from these most interesting martian areas. Then, after a safe journey from Mars to Earth, following all planetary protection constraints, these sample would be analyzed on Earth, using up-to-date chemical, geochemical, and biological tools available. But 5 years is very short, and another option is to directly search for signs of past or even present life on Mars by means of a Mars rover equipped with a powerful scientific payload for astrobiological studies and with a drill for exploring the subsurface.

By the way, this is exactly what the ESA-Roscomos ExoMars mission is planning to accomplish within a largely international mission planned to be launched in 2018, close to 5 years from now…

J. William Schopf

My answer: I know what I would do, but I do not know how I would proceed. In a sense, I have already ''been there and done that,'' and I feel sure that I would follow my earlier path once again. In 1977, I received a huge monetary prize as the recipient of the U.S. National Science Board/National Science Foundation's Alan T. Waterman Award. Given this ''manna from Heaven,'' I had the idea to set up an international team of ''young workers,'' eager imaginative folks of about my same age, to attack unsolved problems of the earliest Precambrian (seven-eighths) of Earth history. With the support of my colleagues, I used the Waterman funds to put together the international and interdisciplinary Precambrian Paleobiology Research Group (PPRG) that has contributed measurably to an understanding of life's early history. I'd do the same thing again and would ensnare young workers, who have new ideas—fresh imaginations, not those ''old guys'' like me—and I would listen to them and learn from them. Then we, as a group, would stride forward.

Norman Sleep

I would sample ice from recently vented water on Mars. The venting by a pingo mechanism was quick, and some microbes likely got entrained in the fluid. One would have to be lucky to get viable organisms, but organic matter would be likely preserved. The known sites are hard to get at. Perhaps a steerable balloon would work.

Werner von Bloh

Direct imaging of extrasolar planets would be one of my primary goals for a $1 billion mission. Such missions have already been planned by ESA and NASA (missions Darwin and TPF, respectively) but have been postponed or cancelled. It will, however, be ambitious to realize one of these missions with the proposed $1 billion constraint. The successful Kepler mission by NASA has already shown that Earth-like planets are a common feature in the Galaxy. Therefore there is a high probability that direct imaging will be successful in finding a habitable world. Direct imaging of extrasolar planets via nulling interferometry would be the next step in detecting and analyzing possible harbors of life. Such a mission will be able to detect possible biomarkers in the atmosphere, showing evidence for life outside the Solar System. Reliable biomarkers have already been identified in order to prevent false-positive results. If the realized space mission will be able to find such a biomarker in a planetary atmosphere, then this will significantly change our mind not only in respect to astrobiological research but also in the general understanding of life as a cosmic phenomenon. But in spite of the uncertainties about the origin of life on a habitable planet, there is a nonzero probability that the mission will fail in finding signs of life on other planets. In mathematical terms, planetary habitability is a necessary but not sufficient condition for life. At least the detection of habitable Earth-like planets can be expected.

Frances Westall

One billion dollars is not sufficient for an astrobiology mission. The most useful astrobiology mission will be to bring relevant samples from Mars to Earth for analysis in terrestrial laboratories. Prior to this we would ideally like to have identified organic molecules in martian rocks and, if possible, made some preliminary identification of a certain compositional complexity in those molecules indicative of a biological origin. However, such a mission would cost 4–5 billion dollars, thus requiring international collaboration and effort.

Abbreviations

GOE, Great Oxidation Event; PNA, peptide nucleic acid; TPF, Terrestrial Planet Finder.

References

Allwood, A.C., Walter, M.R., Kamber, B.S., and Burch, I.W. (2006) Stromatolite reef from the Early Archaean era of Australia. *Nature* 441:714–719.

Bada, J.L. (2004) How life began on Earth: a status report. *Earth Planet Sci Lett* 226:1–15.

Benner, S.A., Kim, H.-Y., Kim, M.-J, and Ricardo, A. (2010) Planetary organic chemistry and the origins of biomolecules. *Cold Spring Harb Perspect Biol* 2:a003467.

Bertrand, M. and Brack, A. (2000) Conformational transition of acidic peptides exposed to minerals in suspension. *Chemistry* 6:3452–3455.

Brack, A. (2001) Water, the spring of life. In *Astrobiology: The Quest for the Conditions of Life,* edited by G. Horneck and C. Baumstark-Khan, Springer, Berlin, pp 79–88.

Brack, A. (2007a) Astrobiology: from the origin of life on Earth to life in the Universe. In *Complete Course in Astrobiology*, edited by G. Horneck and P. Rettberg, Wiley-VCH, Weinheim, Germany, pp 1–22.

Brack, A. (2007b) From interstellar amino acids to prebiotic catalytic peptides. *Chem Biodivers* 4:665–679.

Brack, A. (2010) Searching for a second genesis. In *Astrobiology: Emergence, Search and Detection of Life,* edited by V.A. Basiuk, American Scientific Publishers, Los Angeles, pp 1–21.

Brack, A. (2011) From the love of peptides to the search for life on Mars, an astrobiology itinerary. *Astrobiology* 11:275–279.

Brack, A., Horneck, G., Cockell, C., Bérces, A., Belisheva, N.K., Eiroa, C., Henning, T., Herbst, T., Kaltenegger, L., Léger, A., Liseau, R., Lammer, H., Selsis, F., Beichman, C., Danchi, W., Fridlund, M., Lunine, J., Paresce, F., Penny, A., Quirrenbach, A., Röttgering, H., Schneider, J., Stam, D., Tinetti, G., and White, G.J. (2010) Origin and evolution of life on terrestrial planets. *Astrobiology* 10:69–76.

Chyba, C.F. and Phillips, C.B. (2007) Europa. In *Planets and Life,* edited by W.T. Sullivan III and J.A. Baross, Cambridge University Press, Cambridge, UK, pp 388–423.

Cockell, C.S. and Raven, J.A. (2004) Zones of photosynthetic potential on Mars and the early Earth. *Icarus* 169:300–310.

Heldmann, J.L., Schurmeier, L., McKay, C., Davila, A., Stoker, C., Marinova, M., and Wilhelm, M.B. (2014) Midlatitude icerich ground on Mars as a target in the search for evidence of life and for *in situ* resource utilization on human missions. *Astrobiology* 14:102–118.

Hofmann, H.J., Grey, K., Hickman, A.H., and Thorpe, R.I. (1999) Origin of 3.45 Ga coniform stromatolites in Warrawoona Group, Western Australia. *Geol Soc Am Bull* 111: 1256–1262.

Lineweaver, C.H. and Chopra, A. (2012) The habitability of our earth and other earths: astrophysical, geochemical, geophysical, and biological limits on planet habitability. *Annu Rev Earth Planet Sci* 40:597–623.

Mancinelli, R.L., White, M.R., and Rothschild, L.J. (1998) Biopan-Survival I: exposure of the osmophiles *Synechococcus* and *Haloarcula* to space environment. *Adv Space Res* 22:327–334.

Martin, W.F. (2012) Hydrogen, metals, bifurcating electrons, and proton gradients: the early evolution of biological energy conservation. *FEBS Lett* 586:485–493.

Matrajt, G., Pizzarello, S., Taylor, S., and Brownlee, D. (2004) Concentration and variability of the AIB amino acid in polar micrometeorites: implications for the exogenous delivery of amino acids to the primitive Earth. *Meteorit Planet Sci* 39: 1849–1858.

Maurette, M. and Brack, A. (2006) Cometary petroleum in Hadean time? *Meteorit Planet Sci* 41:5247.

Pross, A. and Pascal, R. (2013) The origin of life: what we know, what we can know and what we will never know. *Open Biol* 3, doi:10.1098/rsob.120190.

Raulin, F. (2009) Planetary astrobiology—the outer Solar System. In *Prebiotic Evolution and Astrobiology,* edited by J. Wong and A. Lazcano, Landes Bioscience, Austin, TX, pp 18–28.

Russell, J.M., Hall., A.J., and Martin, W. (2010) Serpentinization and its contribution to the energy for the emergence of life. *Geobiology* 8:355–371.

Shapiro, R. (2006) Small molecule interactions were central to the origin of life. *Q Rev Biol* 81:105–126.

Sotin, C. and Prieur, D. (2007) Jupiter's moon Europa: geology and habitability. In *Complete Course in Astrobiology*, edited by G. Horneck and P. Rettberg, Wiley-VCH, Weinheim, Germany, pp 253–271.

Tice, M. and Lowe, D.R. (2004) Photosynthetic microbial mats in the 3,416-Myr-old ocean. *Nature* 431:549–552.

Wächtershäuser, G. (2007) On the chemistry and evolution of the pioneer organism. *Chem Biodivers* 4:584–602.

Walsh, M.M. (1992) Microfossils and possible microfossils from the Early Archean Onverwacht Group, Barberton Mountain Land, South Africa. *Precambrian Res* 54:271–293.

Westall, F., de Ronde, C.E., Southam, G., Grassineau, N., Colas, M., Cockell, C., and Lammer H. (2006) Implications of a 3.472–3.333 Gyr-old subaerial microbial mat from the Barberton greenstone belt, South Africa for the UV environmental conditions on the early Earth. *Philos Trans R Soc Lond B Biol Sci* 361:1857–1875.

Westall, F., Cavalazzi, B., Lemelle, L., Marrocchi, Y., Rouzaud, J.N., Simionovici, A., Salomé, M., Mostefaoui, S., Andreazza, C., Foucher, F., Toporski, J., Jauss, A., Thiel, V., Southam, G., MacLean, L., Wirick, S., Hofmann, A., Meibom, A., Robert, F., and Défarge, C. (2011) Implications of *in situ* calcification for photosynthesis in a ~3.3 Ga-old microbial biofilm from the Barberton greenstone belt, South Africa. *Earth Planet Sci Lett* 310:468–479.

Wu, D., Wu, M., Halpern, A., Rusch, D.B., Yooseph, S., Frazier, M., Venter, J.C., and Eisen, J.A. (2011) Stalking the fourth domain in metagenomic data: searching for, discovering, and interpreting novel, deep branches in marker gene phylogenetic trees. *PLoS One* 6, doi:10.1371/journal.pone.0018011.

Yang, Y., Itahashi, S., Yokobori, S.-I., and Yamagishi, A. (2008) UV-resistant bacteria isolated from upper troposphere and lower stratosphere. *Biol Sci Space* 22:18–25.

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