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EANA trail guide in astrobiology: search for a second genesis of life

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Abstract: The European Astrobiology Network Association (EANA) coordinates and promotes astrobiology in the 17 European countries that are member of the organization. Astrobiology includes the study of the origin, evolution and distribution of life in the Universe. It is a multi-disciplinary science that encompasses the disciplines of chemistry, biology, palaeontology, geology, atmospheric physics, planetary physics and stellar physics. The open questions to be addressed and the steps ahead in cosmochemistry, star and planet formation, the chemistry of life's origin, the study of bacterial life as a reference and the search for habitats and biosignatures beyond the Earth are presented.

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Science background

Terrestrial life represents the only example of life known to us. In a first approach, it constitutes a useful reference when searching for a second genesis of life, either in the Solar System on planets, such as Mars or Europa, or on exoplanets. Terrestrial life – defined as a chemical system capable of self-reproduction and of evolution – originated from reactions involving reduced carbon-based organic molecules in liquid water. However, the nature and the complexity of the organic molecules that began to self-reproduce and to evolve are still not known. The problem on Earth is that geological processes, such as plate tectonics, have erased rocks that could have contained relevant information. The chances of understanding the emergence of life on Earth by recreating a similar process in a test tube will obviously depend upon the simplicity of the chemical reactions leading to life. The discovery of a second genesis of life on another celestial body would strongly support the idea of a rather simple genesis of terrestrial life. The possibility that life may have evolved on Mars during an early period when water existed on the surface, and the possibility that life may still exist deep below the surface, marks it as a prime candidate in the search for life beyond Earth. In the outer regions of the Solar System, cryovolcanic flows at the surface of Europa point to a possible subsurface ocean of water and to the possible existence of hydrothermal vents, which might harbour a basic life form. The recent discovery of the exoplanets opens the search for extraterrestrial life to the whole Universe.

The search for a second genesis needs to be developed along the following lines.

1. Cosmochemistry: chemistry in star and planet-forming regions, cometary chemistry and meteorites.
2. Star and planet formation to identify possible habitats, not only in the habitable zone as usually defined in terms of any water being liquid at the surface, but also beyond the habitable zone, such as within tidally heated satellites (such as Europa) and in the interiors of substantial Earth-like bodies where internal heat sources are significant.
3. The chemistry of life's origin: the ingredients of life; the chemical search for self-sustaining, self-containing and self-replicating systems capable of autocatalytic growth, evolution and chiral symmetry breaking. Chemical causes of biomolecular structure, function and system integration.
4. Terrestrial life as a reference: the aqueous cradle of life: early Earth geology, hydrosphere and atmosphere, ancient life (microfossils, morphological, geochemical and isotopic and other biosignatures) and the limits of bacterial life on Earth;

5. The search for habitats and biosignatures beyond the Earth, including Mars, Europa, Titan and extrasolar planetary systems.

Cosmochemistry

Cosmochemistry investigates the chemical cycles occurring throughout the universe, including the formation of elements within stars and during late-type star evolution, their assembly into molecules and dust and the subsequent formation of stars and planetary systems. One of the prerequisites for life is the presence of 'biogenic' elements such as hydrogen, carbon, oxygen and nitrogen. Those elements are formed in the cores of stars by nuclear fusion. Recent data from cosmological studies indicates that primordial star formation may have occurred as early as 200×10^6 years after the Big Bang. It is thought that these objects produced the first heavy elements, although with a different nucleosynthetic signature to those produced by later generations of stars. Carbon monoxide (CO), the most abundant carbon-based molecules in space, was already abundant $\sim850\times10^6$ years after the Big Bang, as demonstrated by recent measurements of a distant quasar.

The interstellar medium plays a pivotal role in the formation and distribution of biogenic elements and in the subsequent production of molecules in the galaxy. Interstellar clouds also provide the raw material for the formation of stars and planets. Our Solar System was formed from interstellar dust and gas, which collapsed to form the Sun, and a surrounding disc, which subsequently developed into our planetary system. Rocky planetesimals formed in the inner zone of this disc, eventually growing into terrestrial planets. The outer Solar System is dominated by giant gaseous planets. Comets and asteroids represent the remnant planetesimals that were not incorporated into planets and their moons, but were instead forced into orbits (e.g. the asteroid belt between Mars and Jupiter), or were ejected into cometary reservoirs in the outer solar system and beyond by gravitational interaction with the gas giants. Rocky remnants from planetary formation were present in high abundance in the early inner Solar System where they collided frequently with young planets, thereby introducing large amounts of extraterrestrial carbon to planetary surfaces.

There is strong evidence that a combination of exogenous and endogenous sources provided the first building blocks of life on the early Earth. The idea that complex organic material of extraterrestrial origin could help to initiate prebiotic chemistry on rocky terrestrial planets links galactic cosmochemistry with other scientific disciplines, such as geology, paleontology and biology, under the interdisciplinary umbrella of Astrobiology. Comets, asteroids and their fragments such as meteorites and interplanetary dust particles (IDPs) are potential sources of water, carbon, nitrogen and complex organic molecules to the early Earth. The study of those sources and the characterization of the organic matter which was exogenously delivered to the early planets allows us to monitor the nature of the kind of material arriving on the early planetary surfaces and to identify chemical processes relevant in their assembly into 'living cells'.

Open questions to be addressed in order to understand the fundamental principles of carbon chemistry in space and its relation to the development of life on Earth include:

- when were the first biogenic elements formed?
- what are the principal reservoirs of carbon in different interstellar environments?
- how complex are the organics that are present in molecular clouds?
- how are high- and low-mass protostars formed?
- when did the first planetary systems form?
- how is interstellar organic matter preserved and/or processed during solar system formation?
- how did impacts and extra-terrestrial delivery of organic material affect the early planets?

Current and future ground-based and space-based observatories will strongly enhance our knowledge of the fundamental processes of astrochemistry and the prospects for detecting more astronomical biomolecules. The role of exogenous delivery needs further investigation and important information on the organic composition of primitive solar system bodies, similar to those that bombarded the early Earth, should become available from the ROSETTA comet rendezvous mission to Comet 67P/Churyumov-Gerasimenko and the STARDUST sample return mission to Comet Wild. Theoretical studies, laboratory experiments, ground and space-borne observations, as well as challenging *in situ* analysis and sample return on and from the above-mentioned key objectives will lead to a fundamental increase in our understanding of how the origin of life, as we know it, could have originated on other planets/moons in our Solar System and beyond (Ehrenfreund *et al.*, 2002; Ehrenfreund *et al.*, 2004).

Star and planet formation

Understanding how stars and planets form and how they evolve in time is important in order to identify habitable places.

Objective 1: Formation of the first stars

The first generation stars were formed in unique conditions from a simple mixture of hydrogen and helium. No heavy elements were present. Taking into account the relevant gas dynamics, chemistry and radiative transfer, we are able to model how the first stars formed. Simulations predict that gigantic stars formed, each containing between 50 and 300 $M_\odot$, they lived fast and died in an extraordinarily brilliant supernova explosions. Heavy elements produced in first stars would change the conditions for future star formation.

Understanding the formation of the first generation of stars will require continued theoretical effort and advance observational techniques in order to detect the light from the first stars. The James Webb Space Telescope (JWST) should be able to observe even modest birth rates of stars out to redshifts $z = 20$ and to see directly the first supernovae.

Objective 2: Star formation history of the Universe

The discovery of starburst galaxies in the early Universe gave us an opportunity to understand star formation in a very different environment from that with which we are familiar with in our own Milky Way. The main challenge here is to find out how these galaxies manage to convert so much gas into stars so efficiently and in such a very short time.

Measuring the rate at which stars formed at different times in the history of the Universe allows us to account for the integral population of stars and stellar remnants as well as the overall abundance of heavy elements that were produced by the stars. This information is essential for understanding the process of planet formation.

Objective 3: Star formation processes

Molecular clouds are the sites of star formation. One of the major unknowns of the star formation process is how a molecular cloud with 10^5 $M_\odot$ of gas forms individual cores of the order of 1 $M_\odot$, out of which individual stars form. The origin of stellar masses is of extreme importance because once the mass of a star is fixed its future evolution is determined and its influence on the surrounding environment is known. Models of turbulent molecular clouds show that their supersonic internal motions lead to the formation of structures. Sub-millimetre continuum mapping of molecular clouds shows that the cloud cores follow a mass distribution similar to the stellar initial mass function (IMF). Giant molecular clouds generally give rise to clustered star formation, whereas smaller molecular clouds tend to form smaller numbers of isolated stars. Very small clouds in relative isolation, known as Bok globules, have turned out to be important laboratories for the study of protostellar collapse.

The current view of low-mass star formation holds that the starless and prestellar core phases together last a few 10^6 years. The Class 0 (when more than half of the total mass of the envelope accretes to the prestellar core) lasts a few 10^4 years and the Class I stage (when less than half of the total mass of the envelope accretes) lasts a few 10^5 years. Once almost all of the envelope has been accreted, the source is called a Class II source or classical T Tauri star. The cirumstellar disc present at this stage may go on to form planets. Next, when the inner part of the disc has dispersed, the source is known as a Class III object or a weak-line T Tauri star. It is likely that our Sun has followed such a route. The Solar System is, of course, the most comprehensively studied planetary system and we are very interested in obtaining information pertaining to its further evolution. The scenario of star formation depends strongly on our understanding of dust properties. Recent observations using balloon-borne experiments have shown that the emissivity of dust appears to be a strong function of dust temperature and of gas density. Newly formed dust also appears to have a higher value of emissivity than dust in the general interstellar medium.

The formation of high-mass stars is less well known than that of low-mass stars. A number of indirect methods have been used to find objects that may be the high-mass analogues of Class 0 objects. At present we know one example of a planetary system that might be the outcome of high-mass star evolution – the pulsar planets around PSR B1257+12.

Objective 4: Formation of very-low-mass stars and brown dwarfs

Brown dwarfs contribute little to the luminosity of their host galaxy; however, given their masses occupy a range between low-mass stars and giant planets, they contribute significantly to our understanding of star and planetary formation. The main questions are: do they form as solar mass stars, are they stellar embryos whose further growth is prevented by dynamical ejections from small stellar systems or do they form like planets within circumstellar discs? All three mechanisms might be at work and they do not need to be exclusive. Isolated brown dwarfs could be the result of gravitational contraction of a small cloud fragment and/or ejection from a nascent star cluster. Brown dwarfs in binaries presumably formed from the stellar nebula by gravitational instability. Some giant planets might also form in this way, while others may form from an initial icy-rocky kernel and a subsequent gas capture process. The important contributions to this subject will come from the studies of circumstellar discs discovered around sub-stellar objects and the discovery of extremely cool dwarfs of spectral type L and T. The existence of circumstellar discs, similar in properties to those found around low-mass pre-main sequence stars (T Tauri stars), suggests that brown dwarfs form from core collapse. In order to constrain the formation mechanism of brown dwarfs we need to study disc accretion properties and discs statistics in a large sample of spectroscopically confirmed young brown dwarfs. If proto-brown dwarfs really exist, SCUBA2 on the JCMT and the Spectral and Imaging Receiver (SPIRE) bolometer array on Herschel will identify a large number of such objects in the nearest star-forming clouds.

Objective 5: Discs – from protoplanetary to planetary discs

Discs are the most likely sites of planet formation giving rise to extrasolar planets. In the standard theory, planet formation occurs through a number of key stages. New developments in giant planet formation theory include models of layered protoplanetary discs and the idea that long-lived vortices in a turbulent protoplanetary nebula can initiate the formation of planets. The global modelling of dust and gas evolution in protoplanetary discs should follow. There are already a few simple examples of such calculations.

Dusty plasmas, perhaps the fastest growing area in plasma physics, might also be of extreme importance for the theory of protoplanetary discs. The term 'dusty plasma' is used when the number of grains in the Debye sphere is greater than one. Theoretical models for the interaction of giant protoplanets with protoplanetary discs show that large low-density gaps can be created within the disc. The detection of these gaps would provide strong support for planetary formation theories but current observations do not have the spatial resolution to directly image the astronomical-unit (AU) sized gaps that are predicted. Further instrumentation, such as Atacama Large Millimetre Array (ALMA), may allow direct detection of such gaps.

Significant progress has been made in the observational, statistical and theoretical interpretation of planetary (debris) discs. Around 25% of main sequence stars in the solar neighbourhood have such discs. They are associated with main sequence stars that are beyond the T Tauri phase. Clearly, these debris discs bridge neatly into the proto-planetary discs on the younger side and into the Sun's zodiacal cloud on the highly evolved side. The first extrasolar debris disc was discovered by the Infrared Astronomical Satellite (IRAS) satellite around the bright star Vega. Recently, the debris around a G2V star – HD 107146 – the same stellar type as our Sun, has been discovered. The SCUBA camera on the JCMT mapped the disc at 450 and 850 μm. These observations imply the presence of a large inner hole around the star. The case of HD 107146 is of particular anthropomorphic interest because it is the closest analogue to the early Solar System yet known. It is like looking at our Solar System as it may have been when 100 Myr old. Special emphasis will also be placed on detecting the existence of inner disc holes caused by dust coagulation in other objects and on tracing the evolution of such holes.

Objective 6: Planets and planetary systems

We have only recently developed the tools to find planets around solar-type stars. The planets around HD 114762, 51 Pegasi, 47 Ursa Majoris, 70 Virginis and Lalande 21185 are just a few examples. Most of these planetary objects have masses comparable to that of Jupiter, orbital semi-major axes in the range of 0.04–5.9 AU and orbital eccentricities between 0 and 0.67 (with one exception, namely HD 80606 b, which has an orbital eccentricity of 0.927). There are also three cases of directly imaged sub-stellar objects: a giant planet orbiting a brown dwarf at a distance greater than 55 AU, a planet (or a brown dwarf) orbiting a young T Tauri star GQ Lup at a distance of around 103 AU and finally a planet (or a brown dwarf) very far from its host star AB Pic (275 AU, about nine times further than Neptune is from the Sun). Thus the orbital characteristics of many of the known extra-solar systems contrast strongly with the gas giants of the Solar System. In order to explain the existence of gas giants very close to their host stars, so called 'Hot Jupiters', the hypothesis of planetary migration has been introduced and several simulations have been performed. It has been found that the interaction of the planets with the gaseous disc works reasonably well as a driving mechanism for migration. The most important task is to search for evidence that this really occurred in the exoplanets. Currently, several multiple-planet systems have been detected including three that show a mean motion resonance. Such a situation is expected in a multiple-planet system in which orbital semi-major axes change through dissipative processes.

The next few years will provide further quantitative information on the distribution of planetary masses and distances from parent stars for planets with sizes between that of Jupiter and Uranus and down to Earth size. Now, if confirmed, the minimum-mass limit for the planets around solar type stars is already around 6 $M_{\oplus}$ (Gliese 678 d). Answering the question of whether Earth-sized planets are common or rare will require advanced instruments, such as Corot, Kepler, SIM, Darwin and the Terrestrial Planet Finder.

The detection of a strong correlation between the metallicity of the star and the probability that the star has a planetary system brings us back to the question of the overall abundance of heavy elements that were produced by the stars during the history of our Universe.

The chemistry of life's origin

The organic molecules required for the appearance of terrestrial life might have been formed in the Earth's atmosphere, in submarine hydrothermal systems or may have been delivered to the Earth via extraterrestrial materials, such as interplanetary dust. Schematically, the prebiotic resources needed for the emergence of life can be compared to parts of a chemical automaton. By chance, some parts assembled to form an automaton capable of assembling other parts to form a second identical automaton. From time to time, a minor error in the assembly process generated more efficient automata. Since the oldest fossils of micro organisms discovered so far have been identified in geological horizons associated with, or influenced by, hydrothermal systems, either sub-aerial or submarine, it is reasonable to consider that the automata were driven by thermal energy, at about 80 °C. The automata had therefore to protect themselves against hydrolysis that was also boosted by the high temperatures. They probably faced this difficulty by growing on, or within, mineral surfaces such as sulphides and/or clays.

The steps ahead

The descriptive nature of molecular biology does not allow us to draw any good conclusions on how life originated on this planet from simpler chemical precursor systems, or, on how life may have originated elsewhere in the universe, nor, whether new forms of life can be synthesized *de novo* in the laboratory. A new science is required that needs to combine the 'classical' knowledge of chemistry and physics, namely the language of molecules, their reactions and interactions, together with the 'classical' knowledge derived from existing forms of life. One key component of this new science, acting both as a translator and abstractor between these languages, may come from the field of theoretical biology, automata theory and complex systems research. The other key component must come from a new chemistry that is the offspring of both, supramolecular and prebiotic chemistry, but adds a new dimension that has not been sufficiently addressed so far. Over the past decade, more and more chemists have learned to design simple self-replicating and self-reproducing systems and today we even have the first examples on the issue of chiral symmetry breaking in autocatalytic reactions. What seems to be missing here is a kind of generalization of 'synthetic methods' based on the principles of supramolecular self-organization, autocatalysis and molecular information processing that are applicable from small molecules via nano- to mesosystems.

Thus the quest is for general recipes to generate chemically coupled autocatalytic systems. This approach complements the emerging field of 'synthetic biology'. Whereas the latter aims at the utilization of intracellular regulatory networks as biological building blocks to construct synthetic cells, the former aims at finding the chemical roots of such regulation in non-evolved systems. 'Protocells', 'chemotons' and 'minimal cells' are just different words for the same field of research that may be biology-driven as a top-down approach or chemistry-driven as a bottom-up approach. In any case, the disassembly and reconstruction approach of synthetic biology means the existence of biological building blocks as the products of biological evolution. Even if synthetic biology will be able to generate a more primitive form of cellular life, this does not necessarily answer the question of how primitive cells could emerge when starting from scratch. Unfortunately, the same fundamental problem underlies our current vision that directed evolution will help to reconstruct a preceding biochemistry, such as the Ribonucleic Acid (RNA) world. Finding a set of self-replicating RNA molecules that cooperate in a vesicle to constitute a minimal cell will be a remarkable scientific achievement in the 21st century. Nevertheless, the question remains of how such a thing could have developed in the absence of evolved 'tools', such as polymerases.

Clearly, the origin of Darwinian evolvability is one of the central challenges in the emerging field that sooner or later may carry names such as 'creation chemistry', 'chemical biogenesis' or 'autogenerative system chemistry'. The other equally challenging frontier is the origin of a sufficiently complex chemically organized system embodying a minimal living, namely self-containing and self-sustaining, entity. All life that we know today is based on cells as the unit of life. The distinction between a unit of life and a unit of evolution may be made for present-day life; however, it is questionable whether any reasonable definition on the origin of life can be made without equating the living state of matter with an evolvable state of matter. If so, the task is to find answers as to what sets of molecular structures, reactions and interactions are required to arrive, finally, at a system that fulfils both the criterion of minimal life and minimal evolvability. The transition from limited to unlimited heredity is then a later issue of research dealing with life's origin.

Life today is based on proteins, nucleic acids, lipids, sugars, amino acids and other molecular building blocks, where almost all molecular components are in a homochiral, namely an enantiomerically, pure state. The creation of minimal life and evolvability is thus necessarily connected to the question of at what level in the transition from small molecules to minimal living and evolving systems the amplification of homochirality took place. Currently, it seems very likely that this process might be deeply linked to the emergence of self-replication and was even indistinguishable from the latter in the beginning. Whether an autocatalytic transformation of racemizing building blocks or a mutual annihilation of autocatalytic products of opposite handedness played a leading role, or whether the building blocks were racemic (as in the formose reaction) or prochiral are open questions to which chemistry must find more answers in the future.

A primary problem here is that we do not even know the repertoire of organic molecules delivered from space or endogenous sources, or what was the initial set of chemical reactions that started the long transformation from space molecules to the first living systems. So long as this question is not fully answered by astrobiological research, any 'primitive' organic or inorganic chemicals may be employed in the design and exploration of chemical systems that hopefully express dynamic signatures of the living systems. The good news is that research in autocatalytic systems currently gains much attention in various areas of chemistry and that the acceptance to work with 'complex mixtures' of molecules has increased since the advent of combinatorial chemistry. What is still a challenge for present day chemistry is to filter out the signal of self-organization in the noise of the numerous side reactions. Gaining chemical control to a whole network of reactions having an autocatalytic 'core' at a low level of information content but otherwise just producing 'diversity', namely a rich mixture of constituents and stereoisomers, is clearly a challenge. For example, being able to 'steer' the formose reaction to produce ribose selectively instead of a diversity of other sugars could be a major breakthrough, because it would change our picture of the plausibility of the RNA world hypothesis almost instantaneously. All that is needed could be a selective consumption of ribose by a coupled (autocatalytic) process that does not allow further breakdown of the ribose skeleton once it is 'protected' at the level of the autocatalytic product. Lipid chemistry has a rich potential for establishing such 'secondary' autocatalytic reactions due to the rich supra-molecular chemistry induced by phase transitions at the nano- and mesoscale. Coupling lipid and self-replicating template chemistry could therefore be another field of research.

Generally, the art of synthesizing *coupled autocatalytic systems* points to the future of chemical research inspired by the origin-of-life problem. Coupling necessarily involves more than one class of molecules. Thus, not only nucleotides or peptides or sugars or lipids but nucleotides *and* peptides, nucleotides *and* lipids, sugars *and* peptides, peptides *and* lipids, to name only a few possible combinations. The exploration of couplings between an autocatalytic core, such as the formose reaction, a self-reproducing micelle or a self-replicating template does not necessarily require that the set of reactions 'talking with the core' are autocatalytic by themselves, i.e. constituting an independently running autocatalytic cycle. Chemoton theory suggests that any reaction triggered by the core autocatalyst, for example in the sense of heterocatalysis, will also cause multiplication and growth of those compounds generated due to the presence of the autocatalyst. Thus the outcome of such coupling manifests in a stoechiometric relationship between the number of 'core autocatalysts' and the number of molecules coming up in the 'periphery' of the reaction network. If the whole process is now selectively generating a specific set of molecules that are different from the mixture in the absence of coupling, information 'harvesting' takes place. As self-replication can be defined as autocatalysis *plus* information transfer, selecting specific products from an autocatalytic network means self-replication. Of course, templating is one of the best proven ways for establishing a mechanism of information transfer but the term 'template' may have a much broader meaning in the future than it had in the past. The same extrapolation may be foreseeable in the issues of evolvability and 'cellular compartilization'.

The European trail guide for chemical and astrobiological research dealing with the origin of life thus cannot be a 'narrow' one. There is so much open room for new chemistry that any attempt to limit the scope might be unwise. However, it makes sense to organize the endeavour along a number of established lines that do already work in practice. The European action on prebiotic chemistry and early evolution (COST D27) names the following topics of research, which are fully compatible with EANA's view: prebiotic chemistry of small molecules, origin and evolution of biopolymers, origin of homochirality, bioastronomy and cosmochemistry, self-assembly, self-organization, self-replication and self-reproduction, directed chemical evolution and the origin of genetic code (Brack, 1998; von Kiedrowski, 2001; von Kiedrowski *et al.*, 2003; Ball, 2003).

Terrestrial life as a reference

The only example of life known to us is life on planet Earth. The study of its diversity and limitations is essential in order to provide us with a database from which to search for a second genesis of life, either in the Solar System on planets or satellites such as Mars or Europa or on exoplanets (Seckbach, 2004). Life is known to exist in almost every type of environment present on Earth, with the exception of hot incandescent lava and high temperature (~113 °C) hydrothermal fluids. Although there is a plethora of life forms on the planet, the majority of them are microscopic, single-celled organisms, most of which are at present unculturable and are only known from gene sequencing analysis. The evolution of sophisticated, multi-cellular organisms appears to be related to the geological co-evolution of the planet and, especially, the appearance of oxygen in the atmosphere. The range of species diversity and evolution thus requires the existence of specific environments that appear at certain intervals during the lifetime of a planet. For instance, the appearance of organisms with technological capabilities occurred roughly about half way through the main-sequence lifetime of the Sun. Thus, although the conditions for the appearance of a simple form of life may be relatively common in the Universe, those required for further evolution are probably relatively rare. In fact, the environmental conditions of the present day Earth should be considered as 'extreme', since those of the early, anoxic planet were normal when life arose and are probably those of other planets where life could have arisen and still exists. It is therefore important to study the environment of the early Earth and the life forms that inhabited it, as well as to try to pinpoint the fundamental stages in life's evolution and the geological/environmental changes that allowed these evolutionary changes to take place. There are a number of problems inherent in such a task. First, there is little material left from the early days of Earth's history and, second, there is great controversy relating to its interpretation (whether relating to the geological context or to the identification of traces of life).

The steps ahead

Primitive Earth and inhabitants

- Make detailed studies of the geological evolution of Earth through time and especially of the earliest period in Earth's history, before the appearance of a significant amount of oxygen in the atmosphere (Gargaud *et al.*, 2005).
- Determine the possible habitats on early Earth and the required environmental parameters (temperature, pH, salt concentration, radiations, carbon, redox couples, etc.).
- Understand the signatures of life relevant for different stages of evolution and create a database that can be used for comparison with eventual signatures obtained from other planets. This database should comprise data from present organisms and include (at least): chemical composition (e.g. lipids), morphological information (e.g. from scanning electron microscopy, Matrix Assisted Laser Desorption Ionization-Time of Flight (MALDI-TOF), Fourrier Transform Infrared Spectroscopy-Mass Spectrometry (FTIR-MS)) and geochemical information (e.g. isotopes) of extant cells and fossil cells (Westall, 2005).

Present extremophilic life

- Continue the studies on the diversity and limits (physiochemical, geographical) of extant life, including exploration of yet unexplored biotopes, particularly in anaerobic zones.
- Document the extremophiles discovered and include the data in the database recommended above.
- Study their survival mechanisms beyond their minimal and maximal conditions (including space conditions) and document any eventual changes occurring in their biosignatures. This is important for planetary protection issues, false positives, etc.
- Study their interactions with their mineral environment at the micrometre scale (chemical modifications of surroundings, cell prints, etc.).
- Include microbiologists, geologists and geomicrobiologists expert in extremophiles in any working group dedicated

to planet exploration, since if life existed or still exists on Mars or elsewhere it is probably similar to present extremophile life on Earth (Horneck and Baumstark-Khan, 2001).

Search for habitats and biosignatures beyond the Earth

Until 1995, when the first exoplanet around a solar-type star was detected, the question as to whether planets existed outside our Solar System was hypothetical. As of May 2005, 155 planets in more than 136 exoplanetary systems have been discovered. With the discovery of planets in other stellar systems, science is continuing the Copernican revolution, placing our planetary system among a wealth of systems existing in the Universe.

One of the major questions to be answered – of interest for astronomers, planetologists and biologists, as well as for the general public – is whether life may have evolved on a habitable terrestrial exoplanet outside our Solar System. However, before studies of the biological evolution of a potential biosphere can be considered, knowledge of the physical environments of possible 'habitable' exoplanets is fundamental.

The search for terrestrial exoplanets has been identified in the long-term plan of the European Space Agency (ESA) as the first of its 20 priority actions. For this reason, the search for and the study of terrestrial exoplanets has become ESA's top priority for the planned Space Interferometry mission Darwin, with high spatial resolution astrophysics as a secondary objective. The current planning of the ESA foresees a launch of Darwin no earlier than 2014. To understand the principles that generated the Earth's environment and its long-term habitable conditions and to study similar terrestrial extrasolar planets, space missions, such as Darwin and NASA's Terrestrial Planet Finder (TPF) (launch foreseen in the second decade of this century) and their precursors such as COROT (CNES, launch 2006), Kepler (NASA, launch 2007) and Space Europe's Astrometry mission, GAIA, are currently under development.

The main aims of the Darwin and TPF missions are as follows.

- To investigate the prevalence of Earth-like planets in habitable zones around a large enough sample of the nearest solar-like stars to be able to tell us the frequency of occurrence of such planets.
- To determine the status of our own Earth in this scenario.
- To investigate the conditions and evolutionary status on any planet found. If a sufficiently large number of planets are detected and can be studied, they will tell us how frequent the evolutionary scenarios we observe in the solar system are, as well as teach us about different evolutionary pathways.
- To search the spectra of any detected planetary atmosphere for signs of what are commonly called bio-markers (i.e. signs of biological activity as we know it), or their precursors.

A clear understanding of exoplanetary atmospheres and predictions of the kind of spectral signatures to search for in ground-based or space-based observations is of vital importance for answering the question of whether Earth-like planets exist elsewhere.

The question of atmospheric stability against atmospheric escape is another major topic to be investigated. Only atmospheres stable over long time-spans will allow the development of a surface biosphere. A key point of the investigations will be the translation of the developed biospheric models into observational quantities, determining optimized observational approaches to detect atmospheric signatures of extrasolar planets. Testing several observational techniques with currently existing instrumentation will be a complementary goal to the modelling efforts.

In order to fulfil these requirements, closely interacting interdisciplinary scientific communities, such as those represented in EANA, are required to address the scientific needs of future planet-finding space missions and for the detection of bio-markers on Earth-like exoplanets (Brack *et al*., 1999; Brack and Leclercq, 2003; Gilmour and Sephton, 2003; Jones, 2004; Clancy *et al*., 2005).

Conclusion

The discovery of a second genesis of life on another celestial body might point the way to life as a universal phenomenon that appears whenever certain conditions are fulfilled. In addition to its scientific interest, such a discovery would represent a major breakthrough as well as having deep philosophical implications.

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