Astrobiology: origin, evolution and distribution of life in the universe.

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Astrobiology studies the origin, evolution, distribution and future of life in the universe (fig 1). Astrobiology is multidisciplinary and brings a common, biological perspective to such diverse fields as astronomy, astrophysics, biochemistry, chemistry, ecology of extremophiles, geology, microbiology, molecular biology, palaeontology, physiology, planetary sciences, prebiotic chemistry, space exploration and technology, without omitting law and philosophy. Recent and future exploration in the solar system and beyond offers new opportunities to investigate the possibility of life beyond Earth.

What is life? Life can be defined as a suite of chemical processes enclosed in a compartment (the cell), exchanging energy and matter from the environment and transforming it (metabolism), reproducing by transfer of its information material (genes) to its descendants, and evolving (transferring information about new adaptations or advantageous accidental mutations). Necessary ingredients for life include liquid water, chemical elements and energy source, on a geologically active planet. Although the conditions necessary for life to emerge on a planet might require more than simply mixing a few ingredients, it is possible that suitable conditions for life to appear and evolve exist or existed elsewhere in the universe, possibly even in our solar system but maybe not.. Extraterrestrial life would probably be based on C (one of the most abundant element, building complex molecules with high information content), H, O, N in a water solvent, (these elements are the first to form in stellar environments and are ubiquitous in the universe) although possibly presenting very different morphologies. This is life as we know it. Other hypotheses propose an extraterrestrial life using another solvent (liquid methane-although chemical reactions would be very slow at these low temperatures-, liquid Nitrogen, hydrocarbon) and chemical element (Silicium – although this seems difficult as Si cannot form highly complex molecules, these are unstable and the chemical links are more robust and require more energy to be broken in chemical reactions-On Earth, Si is mostly forming silicate minerals). Nevertheless, whatever form life may take, it will most certainly alter the environment in which it thrives, building sedimentary structures, and/or causing imbalance in element cycles (C, S, ..) that cannot be explained only by universal laws of physics and abiological organic chemistry. These biosignatures can be detected on early Earth, present Earth, and soon on planets of our solar system. Instruments deployed on Mars or on returned samples to look for traces of past life should be tested on terrestrial sedimentary rocks where biosignatures are known to be preserved. The early rock record of Mars is better preserved than on Earth due to the lack of tectonic processes and thus is more likely to contain biosignatures, if life ever evolved there.

The search for past or present life beyond Earth requires a solid understanding of life's origin and evolution on the only planet on which life is known -the Earth. Life had a profound effect on the landscapes and atmospheres of Earth possibly since about 3.8 billions years ago (Ga) and let traces or biosignatures (objects, molecules or patterns that can be explained only by biology), permitting the detection of its past or present activities. The presence of stromatolites, microbial mats, isotope fractionation, complex organic molecules, chirality, and fossils permits to track the evolution of our biosphere.

The Precambrian includes the Hadean (4.6 to 4 Ga) (Ga: billion years), the period of solar system formation and Earth accretion, the Archean (4 to 2.5 Ga) when life appeared, and the Proterozoic (2.5 to 0.56 Ga) subdivided into the Paleo-, Meso-, and Neoproterozoic. After (or during) a Late Heavy Bombardment period in the early Archean, life arose on a planet exposed to harsh UV radiation and without oxygen in its atmosphere and oceans, but rich with liquid water, reacting organic molecules, and (hydrothermal, solar, chemical) energy sources. Although liquid water, elements and energy are considered required for life to emerge, the environmental conditions of the origin of life are not understood yet. Also important for life on Earth is the presence of a large moon, which stabilizes our planet's obliquity and help maintain a stable climate over long time-scales. Another crucial factor in stabilizing the climate and keeping our planet habitable (with liquid water at the surface) is the recycling of carbon dioxide and silicates by plate tectonics, the process by which the seafloor is continuously created and recycled. Geological and geothermal activity essential for maintaining climate stability can occur only in a planet with a large enough mass permitting a slowly cooling interior to sustain volcanism and a sufficient gravity field to retain its atmosphere (on the contrary to Mars, which has only one ninth of Earth's mass). The oldest zircons (these minerals must form in water) are dated at more than 4.3 Ga, possibly indicating the presence of an ocean at that time. When the sun formed at 4.6 Ga, it was 30% less bright than today (the so-called"Faint Young Sun Problem"), conditions that would have frozen the Earth without increased concentrations of greenhouse gases such as CO_2 and CH_4. Following this warm period, a step-wise increase in atmospheric oxygen (produced by cyanobacteria) in the Paleoproterozoic around 2.32 Ga would have resulted in oxidation of methane into carbon dioxide and climate cooling, as evidenced by glacial deposits. The oxygenation event(s) also modified the chemistry of early oceans, going from anoxic conditions, to anoxic and sulfidic deep oceans topped by slightly oxygenated surface waters, to more oxygenated conditions. These changing redox conditions in early oceans impacted the patterns of life diversification, possibly by limiting trace elements availability. These early environmental conditions were extreme compared to today's, but might still be common beyond our planet. A large diversity of prokaryotic microbes flourished and still thrives without much change in their morphology, physiology or habitat for 4 billion years. The oxygenation of atmosphere and oceans expanded possible niches for life to diversify. Eukaryotes (nucleated cells) may have been present on Earth for at least 2.7 billion years. In the Neoproterozoic, the fossil record shows evidence for the evolution of eukaryotic multicellularity, heterotrophy, biomineralization and possibly predation. Just before the Phanerozoic, animals take the stage and introduce a new predation pressure onto life evolution.

Extremophiles were among the earliest forms of life on Earth, still thrive today in a wide range of extreme environments, and possibly exist or could adapt beyond Earth. Hence, study of life and the environment on the early Earth, and the identification of the physical and chemical limits of life on the present Earth are critical components in developing missions for planetary explorations and permanent planet stations.

Ongoing exploration of Mars by the European orbiter mars Express, the NASA orbiter MRO, and the NASA MER rovers Opportunity and Spirit, has revealed three steps during the geological evolution of the red planet. From its formation until about 3.7 Ga, Mars had an atmosphere, a magnetic field and liquid water at the surface. Therefore, Mars might have been habitable when life arose on Earth. Following this Noachian period, dramatic changes including violent volcanism, loss of magnetic field and atmosphere produced conditions difficult for life, where acidic saline conditions prevailed in transient pools among dune fields. Today, Mars is a very harsh place, with oxidizing conditions, high radiation rate, and no liquid water at the surface. Future exploration by ESA (the AURORA program, fig 2) and NASA will aim to further characterize the geological and geophysical characteristics of Mars and will look for possible traces of past or even present life, if life ever appeared on our sister planet. Other programs will study the habitability of the Jovian satellites in the solar system, and of exoplanets (Darwin, ESA and TPF, NASA).

However, Astrobiology is not limited to searching life on Mars, Europa or in exoplanetary atmospheres. It is also about understanding life on Earth, and how solar systems form, how planets evolve with or without oceans and atmospheres, and which conditions are necessary for life to emerge. Astrobiology places biology in a planetary context. Evidence of the absence of life will be as important as finding life, in understanding where and why life exists.

Figure 1: Astrobiology: from planets to life (photo: ESA)

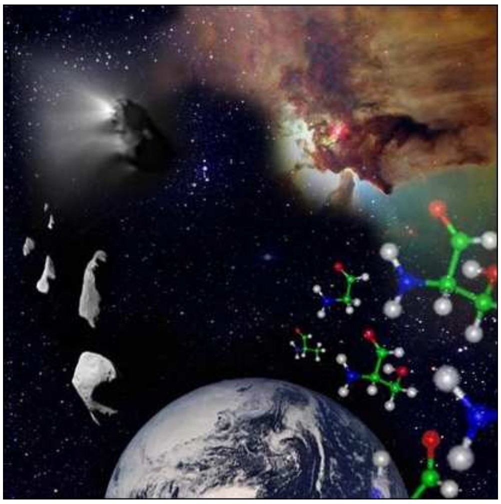

Figure 2: Future exploration of Mars: the AURORA program (photo: ESA)