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Biosignatures for Astrobiology

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Foreword

As a scientific discipline, astrobiology includes the study of life's origin, distribution, and fate in the Universe. By embodying the search for life, astrobiology includes research focused on the study of life's signatures within our Solar System and beyond. Recent discoveries suggest that the Universe is more amenable to life than previously recognized. Hence, the timeliness of *Biosignatures for Astrobiology*, a book edited by B. Cavalazzi and F. Westall, eloquently examines biosignatures in the context of the Earth and Solar System planetary bodies. Earth-like exoplanets are now being detected at a remarkable pace, which is likely to escalate as the Transiting Exoplanet Survey Satellite (TESS) comes online this year and the James Webb telescope to be launched next decade.

The number of interesting planetary targets for astrobiological exploration of extinct and extant life within our own Solar System has also increased as their geologically active nature has been revealed. While it has been known that Mars was potentially habitable early in its lifetime, with large oceans and lakes in abundance, the recent in situ discovery of complex organic molecules preserved in ancient sediments is consistent with the hypothesis that carbonaceous biosignatures could be preserved for long periods of time on the red planet. The recent finding that Mars releases methane seasonally is certainly indicative of the planet's dynamic nature on local scales, regardless of whether it was produced by microorganisms, which portends modern subsurface geochemical activity that could support life.

Evidence of the dynamic nature and habitability potential of other planetary moons in our Solar System has been captured in flyby mission images of geysers on the surfaces of Enceladus and Europa, young icy moons of Saturn and Jupiter, respectively. The incredible images captured by the Cassini–Huygens space probe of liquid methane lakes dotting the surface of Titan reminds us of how little we know about the inventory and distribution of organics in our Universe, a certainty substantiated by the incredible Hubble Space Telescope images of massive star-forming nurseries of the galaxy, regions of space replete with complex organic molecules.

Key to astrobiological exploration for extinct and extant life, whether beyond or within our Solar System, is the search for biosignatures. On Earth, astrobiologists conduct field and laboratory investigations, perform planetary simulations, and generate theoretical models in an attempt to understand how life originated and evolved on Earth. Given the uniqueness of Earth as the only known abode for life, along with the current trajectory of the future of our planet's climate, any improvements in understanding the early evolution of life and the potential for it to adapt to future terrestrial, low-Earth orbit, and eventually extraterrestrial environmental challenges may be essential for our survival as a species.

How life interacts with, and responds to, its environment to produce biosignatures that will be preserved on other worlds is an important thrust of astrobiology. Extremophiles are studied with evermore sophisticated technologies in microbially dominated habitats, in planetary conditions simulated in the laboratory, and in terrestrial samples of their fossilized habitats. These opportunities provide a baseline for testing hypotheses related to understanding what fraction of biosignatures become preserved in the geological record and how best to find, detect, and interpret them. Whether biosignatures of extinct or extant life can be distinguished from abiotic mimics is especially challenging, given the continuous rain of abiotically produced organic matter to planetary bodies throughout the Universe.

The search for biosignatures is compounded by the fact that they range in size from the atomic to planetary scales, and their age could virtually be any age during which life could have inhabited a planet and its biosignatures could have been preserved. On Earth, biosignatures of life were preserved in a variety of geological deposits throughout most of the planet's history. Hence, the amount of alteration that ancient biosignatures on Earth have received may not be directly comparable to that experienced by a similar type of biosignature preserved on another rocky planet like Mars, for example. The correct interpretation of any possible biosignature preserved in the geological record of a planet also requires an understanding of the processes that have altered it since its time of formation.

The book *Biosignatures for Astrobiology* brings together our current understanding of biosignatures with some of the most useful methodologies and technologies used in astrobiology search strategies in an easily readable and comprehensive manner. The book is suitable for the scientifically inclined layperson, the student of astrobiology, and the professional astrobiologist as well. All of the authors contributed background sections to help nascent readers of astrobiology literature grasp the main concepts. In its entirety, the book illustrates why the search for biosignatures beyond Earth is complicated, risky, and a compelling challenge for current and future generations of scientists worldwide. The book is laid out such that it lends itself to be read from cover to cover in sequence or one chapter at a time out of sequence. *Biosignatures for Astrobiology* will be useful for teaching an advanced course in the field or as a reference for practitioners.

The presence of life forms on Earth that have the capability to withstand the harshest of conditions, even those on nearby planets, underscores the hypothesis that life exists elsewhere in the Universe. As stated in the book's final chapter by Dunér, "So far, we have no conclusive evidence of the existence of extraterrestrial life. But could we ever be 100% sure that we are alone?" To be unequivocally sure that no life exists anywhere but on Earth is something we may never know. Yet we are confident that the innate curiosity of humans to know life's origins, and whether it will or does exist beyond Earth, is certain to drive astrobiological exploration far into the future so long as these questions remain unanswered. Even when answers are forthcoming, the field of astrobiology will endure. Surely, if life exists in at least one other place in the Universe, the possibility that it occurs in a third locality is almost a certainty.

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August 27, 2018

Preface

This book on *Biosignatures for Astrobiology* has had a long germination. It started with an article that we wrote on *Biosignatures in Rocks* for the *Encyclopedia of Geobiology* published by Springer in 2009, and early suggestions from Ramon Khanna at the 13th meeting of European Astrobiology Network Association (EANA) in 2013 hosted in Edinburgh.

With the ongoing Mars Science Laboratory Mission to Gale Crater and the ExoMars Trace Gas Orbiter (2016) and lander/rover (2020), as well as the future JUICE and Europa Clipper Mission to Jupiter and its satellites and the various telescopes (HUBBLE, Spitzer, Kepler, TESS, JWST, WFIRST) searching for exoplanets, the time is appropriate to review biosignatures of relevance for astrobiology, addressing all aspects of the discipline. Our book thus aims at capitalising on the latest advances to provide overviews in all the domains of astrobiology.

Since the paradigm-changing discovery of the first exoplanet orbiting a main-sequence star and the finding of highly controversial biosignatures in the Martian meteorite ALH84001 by David McKay and his colleagues in 1996, biosignature research across the board in astrobiology has made enormous advances. Whether or not ALH84001 or other Martian meteorites harbour traces of life, the very idea that microbial fossils could be preserved in a meteorite from Mars sparked a huge interest in biosignature research covering the minimum size of microorganisms, extremophiles, through to the fossilised traces of life, and astrobiology missions to Mars.

We address the signatures of life with respect to life on Earth as well as life elsewhere in the Solar System (i.e. Mars) and exoplanets. For our purposes, we are assuming that the extraterrestrial life forms, hopefully encountered in the future (even if in fossil form), are based on carbon molecules and water as a solvent. Therefore, in order to place the topic of the biosignatures in context, we start with a couple of chapters that “set the scene”. André Brack starts Chap. 1 with an overview of the chemical signatures at the origin of life in which he underlines the basic precepts of carbon and life and the carbonaceous signatures of life, namely an overrepresentation of organics and long strands of homochiral sequences. Since it is widely believed that the majority of the carbon required for the emergence of life on Earth came from extraterrestrial sources, and that the flux of this kind of carbon continues to this day, albeit at a much lower rate than on the early Earth or the early planets and satellites, André Brack's chapter is followed by a contribution from Eric Quirico and Lydie Bonal who, in Chap. 2, review the present state of knowledge on the composition, structure, and formation and evolution of the exogenous organics accreted by the Earth on their original asteroidal or cometary parent bodies. The importance of this knowledge is put into perspective when one considers the fact that, despite the harsh radiation and oxidising environment reigning at the surface of Mars for more than 3 billion years that effectively destroys the more volatile fraction of any organic matter, abiotic (meteoritic) or potentially biogenic, recent, hard-won results from the SAM instrument on the Curiosity rover on Mars do, indeed, show that organic molecules are present in the Martian surface.

Both the MSL and the ExoMars missions hope to find traces of life on Mars, more likely fossil life than extant life. The molecular compounds detected in Gale Crater are important in their own right since it is to be expected that, at a minimum, extraterrestrial carbon should be present at the surface. The continued hope is to find signatures of life. David J. Des Marais and Linda L. Jahnke address biosignatures of cellular components and metabolic activity in Chap. 3. They review life's basic capabilities of energy harvesting, metabolism, and self-replication, which can create objects, substances, and patterns—biosignatures—that indicate their biological origins. They conclude that the simultaneous presence of multiple biosignature objects, substances, and patterns in a demonstrably habitable earlier environment constitutes the most compelling evidence of past life.

Although it is widely believed that the likelihood of extant life forms at the surface of Mars is very low, the idea that life could subsist in the Martian subsurface is gaining credence. In this perspective, Frédéric Gaboyer, Gaëtan Burgaud, and Virginia Edgcomb in Chap. 4 describe very slow living extremophiles found up to several kilometres deep in subsea sediments and emphasise their relevance for the search of biosignatures in the Martian subsurface. The search for life in situ on another planet requires an approach that incorporates systematic preparation in terms of ground- and space-based studies before a mission. Jean-Pierre de Vera and colleagues from the BIOMEX and BIOSIGN experiments provide an overview of the necessary steps in order to search for life in situ on another planet or moon in Chap. 5 and show results obtained from research performed in the field, in the lab, and in space to help enhance knowledge of the traces and signatures of life, and how to recognise life itself. The different kinds of mineralogical traces that can be produced by microbial life forms are described in Chap. 6 by Karim Benzerara, Sylvain Bernard, and Jennyfer Miot. They review the manner in which many organisms impact mineral nucleation and growth, thus producing biominerals with specific chemical, structural, and textural properties that can provide clues to their biogenicity. Taking the concept of mineralisation and the preservation of microorganisms further, Fances Westall, Keyron Hickman-Lewis, and Barbara Cavalazzi make an overview of biosignatures in deep time, concentrating specifically on the oldest preserved biosignatures in well-preserved, although moderately metamorphosed, rocks up to 3.5 billion years old from the greenstone belts of Barberton in South Africa and the Pilbara in Australia. They show that the earliest preserved traces of life record an already thriving and, for an anaerobic world, evolved microbial ecosystem that included anoxygenic photosynthesis.

Indeed, carbonates as biominerals were described by David McKay and co-authors (1996) in the ALH84001 meteorite from Mars as one of the criteria in their interpretation of fossil life in the meteorite. Fractures within the meteorite contain rosette-shaped, aqueously deposited carbonate containing small ovoid to filamentous-shaped objects that the McKay team believed to be microbial nanofossils. Associated with the carbonates are minute magnetite crystals that were interpreted as biominerals produced by magnetotactic bacteria. Harry Y. McSween in Chap. 8 makes a critical appraisal of the original claims and the mountain of experimental data that ensued the 1996 publication, concluding that the evidence for biogenicity is weak.

Continuing on the theme of minerals, John Robert Brucato and Teresa Fornaro look at the role of mineral surfaces in prebiotic processes and life detection investigations focusing mainly on Mars exploration in Chap. 9. They show how molecule–mineral interactions provide important support for space missions aimed at searching for past or present signs of life in the form of molecular biomarkers within rocks.

One way of studying organic molecules as prebiotic or biosignatures in rocks is to look at the effects of photochemistry in space on astrobiologically relevant substrates. These molecules formed part of the organic inventory that was used for the prebiotic processes leading to the emergence of life. In Chap. 10, Avinash Dass, Hervé Cottin, and André Brack review the history of experiments to expose organic molecules to space radiation, observing the kinds of changes that occur in them.

The search for extraterrestrial life concerns not only our nearest planetary neighbour, Mars, but also rocky, Earth-like (or other habitable but not so Earth-like) planets in general. John Lee Grenfell in Chap. 11 provides a brief overview of potential biosignatures of relevance to remote observation and reviews knowledge of the main processes which influence biosignatures in an exoplanetary context, looking specifically at atmospheric model studies for Earth-like planets which predict climate, photochemistry, and potential spectral signals of biosignature species.

Just such a potential atmospheric signature for life has been found on Mars over the last couple of decades. Methane has been measured in the Martian atmosphere from ground-based telescopes, from Martian orbiters, and now in situ by the Curiosity rover. Franck Lefèvre reviews the history of the observations and evaluates their implications for the origin of methane as a possible biogas in Chap. 12.

One of the instruments in the Pasteur payload of the ExoMars 2020 rover is a Raman spectrometer, and another Raman spectrometer will fly on the Mars 2020 caching mission. Frédéric Foucher in Chap. 13 presents an overview of the different types of biosignatures that can be detected and/or characterised using Raman spectroscopy, including organic molecules, microfossils, biominerals, or even living cells.

The search for life on Mars is not new. The two 1976 Viking landers on Mars were the first dedicated astrobiology missions to the red planet. Jorge L. Vago, Frances Westall, and Barbara Cavalazzi in Chap. 14 review the ambiguous results from this mission and introduce the objectives of the ExoMars 2020 rover and its approach to the search for past or present life on the planet.

The final part consists of a philosophical appraisal of the notion of biosignatures by David Dunér in Chap. 15 examines the human search, understanding, interpretation of biosignature natures, the concepts of conceptualisation, analogy, perception, and the semiotics of biosignatures.

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We covered many of the fundamentals in our *Biosignatures for Astrobiology*; however, we would like to emphasise that if we are far away from being complete—always there are questions left without response—we would like to stimulate further discussions and open new perspectives in the research for life.

Bologna, Italy
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May 2018

Barbara Cavalazzi
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